Chapter II

Digitalization trends and the material footprint

The first phase of the life cycle of digitalization is the production of digital devices and ICT infrastructure. This phase covers the extraction and processing of materials, manufacturing and distribution of the digital products, accounting for the largest share of digitalization's environmental footprint.

There is growing demand for minerals and metals needed for the shift to low-carbon and digital technologies, which is part of a broad transformation in the world economy.

This can provide opportunities for many developing countries, provided they are able to add more value to their raw materials. In addition, the environmental and social implications of this production need to be managed. There is a need to reverse structural trade imbalances, wherein developing countries export raw minerals and import higher value-added manufactures, which contributes to an ecologically unequal exchange.

A. Introduction

The digitalization life cycle starts with the production phase, which includes raw material extraction and refining, from which components are produced for the manufacturing of digital hardware and building of ICT infrastructure. The production stage mainly concerns the core digital sector (IT/ICT) included in the overall definition of the "digital economy" (UNCTAD, 2019a: figure I.1).

Within the digitalization life cycle, it is the production phase that has the largest overall environmental footprint (see chapter I). Most studies focus on the environmental footprint in terms of carbon emissions or energy impact. The material footprint of digitalization, which is the focus of this chapter, has received much less attention.[1]

Digitalization was expected to contribute to the dematerialization of the world economy. So far, that promise has not materialized (Creutzig et al., 2022; Dedryver, 2020; Hynes, 2022). Indeed, the increased global material footprint, which has quadrupled since 1970, is a growing concern (Lenzen et al., 2021). The 2024 Global Resources Outlook by the International Resources Panel (UNEP and IRP, 2024) warns that material resource extraction could increase by almost 60 per cent between 2020 and 2060, unless urgent and concerted action is taken to change the way resources are used. This projected increase would far exceed resources required to meet essential human needs, in line with the Sustainable Development Goals.

Moreover, the material footprint is highly unequal. In 2020, it was estimated that high-income countries had the highest material footprint per capita (24 tons), which was close to five times that of lower middle-income countries (5 tons) and six times the amount of low-income countries (4 tons) (UNEP and IRP, 2024).

Further, in assessing nations' cumulative material use in excess of equitable and sustainable boundaries, Hickel et al. (2022: e342) find that "high-income nations are responsible for 74 per cent of global excess material use, driven primarily by the United States (27 per cent) and the European Union 28 high-income countries (25 per cent). China is responsible for 15 per cent of global excess material use, and the rest of the Global South (i.e., the low-income and middle-income countries of Latin America and the Caribbean, Africa, the Middle East, and Asia) is responsible for only 8 per cent. Overshoot in higher-income nations is driven disproportionately by the use of abiotic materials, whereas in lower-income nations it is driven disproportionately by the use of biomass".

Material resources extraction and processing affect all aspects of the triple planetary crisis. They account for 60 per cent of GHG emissions, over 90 per cent of biodiversity impact and 40 per cent of pollution-related health impacts. This is likely to continue due to unchecked resource use and affluent lifestyles in high-income countries, while a significant share of the world's population cannot meet basic human needs (UNEP and IRP, 2024).

However, this exponential surge in demand is raising concerns that it will collide with the limits of finite resources. Increasing costs and efforts for extraction, as discoveries of deposits and mineral ores decline, are resulting in a growing interest in exploring mineral resources in uncharted areas such as in the ocean bed and in outer space. Mineral depletion will require a rethinking of the use of resources and a move

The promise of the dematerialization of the world economy following digitalization has not materialized

[1] Material footprint is defined as the total amount of raw materials extracted to meet final consumption demands. See https://unstats.un.org/sdgs/report/2019/goal-12/.

towards more responsible and sustainable modes of consumption and production.

A transition to low-carbon technologies can only be successful with the support of digital tools, and digitalization needs to be environmentally sustainable

Given this context, this chapter focuses on the material footprint of digitalization, with a particular emphasis on the dynamics of minerals and metals use, and the implications for trade and development. It emphasizes the need to consider the shift to a low-carbon and digital economy as part of a (single) transition, which requires vast amounts of minerals and metals. A transition to low-carbon technologies can only be successful with the support of digital tools, and digitalization needs to be environmentally sustainable. The analysis in this report uses the term "transition minerals and metals", or "transition minerals" for short.

Section B analyses the material footprint of digitalization. Section C reflects on demand projections and possible supply responses related to transition minerals. Section D discusses international minerals markets, which are strongly influenced by geopolitics. Opportunities for developing countries for inclusive and sustainable development outcomes from increased minerals demand are highlighted in section E. Negative environmental and social impacts that mining generates, including on human rights, are presented in Section F. Section G provides conclusions.

B. The expanding material footprint of digitalization

The generalized idea that digitalization, by moving activities from the analogue, physical world to the digital, virtual world will lead to dematerialization, is not matched by reality. The digital society and economy are commonly associated with concepts such as "virtual", "intangibles" or the "cloud", which imply an ethereal world, yet these are far from being dematerialized. Indeed, digitalization is relatively material-intensive, as it involves the use of significant amounts of physical materials, particularly to produce digital hardware or to build ICT infrastructure, not to mention its high energy demands during the use stage (see chapter III).

Estimations of the materials used for digitalization do not abound.[2] This section discusses the material composition of digital devices and ICT infrastructure, focusing on minerals and metals, and presents trends in digitalization that are leading to increased demand for resources that are also needed for low-carbon technologies.

1. The material composition of digital hardware and ICT infrastructure

Digitalization strongly relies on the physical world and involves large amounts of material consumption (UNEP, 2021a), particularly to produce digital devices, including the batteries powering them, and to build digital infrastructure such as transmission networks and data centres (CODES, 2022).

While the digital world is based on data, which are intangible, these data need physical supports. First, the interface between humans and the digital world is enabled through physical devices such as mobile phones or smartphones, personal

[2] For example, Ademe and Arcep (2023) estimates that, on average, a person living in France generates 949 kg/year of resources through ICT use and the production of devices, and 301 kg/year of waste (including electronics and linked to the extraction of raw materials).

computers, tablets, smart televisions and wearable devices;[3] this is how people connect with the digital world in their daily lives. Second, communications and data transmissions pass through infrastructures such as mobile transmission networks, fibre optics, submarine cables or satellites. Finally, the storage of data and cloud services takes place in data centres, which are heavy users of hardware and IT equipment. Some of the largest data centres may contain tens of thousands of servers (Lehdonvirta, 2023).

Digital devices, hardware and digital infrastructure are composed of plastics, glass and ceramics, as well as several dozens of minerals and metals; for instance, Bookhagen et al. (2020) estimate that for a smartphone, metals represent 45 per cent of the total composition, with the display or glass accounting for 32 per cent, plastics, 17 per cent, and other materials, 6 per cent. Moreover, most of the metal value (72 per cent) comes from gold.[4] In economic terms, an analysis of the composition of an iPhone 6 (16 GB) smartphone suggests that the price of the mineral content was about $1 (Valero et al., 2021; Merchant, 2017). However, it is necessary to go beyond economic value and factor in social and environmental externalities.

The analysis in this chapter focuses on the minerals and metals composition of devices and ICT infrastructure, as these raw materials primarily contribute to essential digital, electronic and electric functionalities. Properties of minerals and metals contribute to conductivity, durability and energy density and increase the capacity for energy storage and enable devices to be lightweight. Minerals and metals also have electronic, magnetic, mechanical or optical properties, depending on the mineral or metal used. These materials are of particular importance for developing countries, which are often major producers and exporters of these resources. Other components also have a significant environmental impact, particularly plastics, although they are not as integral to the digitalization process as minerals and metals. Plastics are generally used in overall production processes and used in all countries.[5]

In recent years, minerals have received increased attention, as they have become essential for the functioning of modern societies, particularly for advancing both low-carbon and digital technologies, and especially in the context of mitigating climate change. While there has been much discussion of "critical" and "strategic" minerals (or metals, materials and raw materials) as well as "energy transition minerals", including battery minerals (UNCTAD, 2020), far less attention has been paid to their role in the context of digitalization.

Many countries are adopting the term "critical minerals" and are establishing lists of such minerals or raw materials. However, there is no standard definition of "criticality"; it varies over time and depends on individual country objectives. Criticality generally refers to economic importance and strategic interest, import dependence and vulnerability of the mining supply chain (Hendriwardani and Ramdoo, 2022). These lists mostly focus on the energy aspect of the transition. However, as illustrated in figure II.1, almost

While there has been much discussion of "critical" and "strategic" minerals and metals, far less attention has been paid to their role in digitalization

3 Given the rapid evolution of digital technologies, the definition of what is a digital or electronic device is a moving target. For example, while some years ago a television would not have been considered a digital device, at present, smart televisions can qualify as such. Similarly, as cars are increasingly based on electronics rather than on mechanics, they are becoming "computers on wheels"; according to Accenture (2022), an automobile may contain between 1,000 and 3,500 semiconductors.

4 According to another estimate of the composition of smartphones, plastics and synthetics account for 30 to 50 per cent of the materials, glass and ceramics represent 10 to 20 per cent and metals represent 40 to 60 per cent (Berthoud, 2021). See also https://www.dailymail.co.uk/news/article-10727189/How-ton-iPhones-300-times-gold-ton-gold-ore-REALLY-screen.html.

5 Recent work by UNCTAD in relation to plastics is available at https://unctad.org/data-visualization/global-plastics-trade-reached-nearly-1.2-trillion-2021 and https://unctad.org/news/how-build-concerted-multilateral-action-plastic-pollution. See also UNCTAD (2023b).

all materials deemed critical hold significance for both digital and low-carbon technologies, with the exception of potassium.[6]

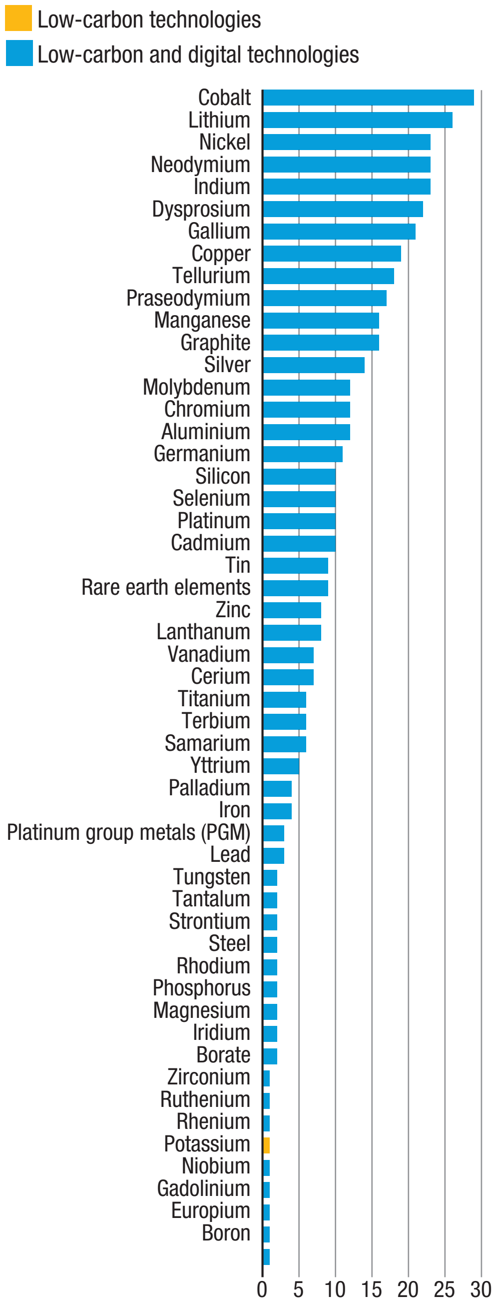
As noted, this report takes a broader approach than is generally seen and addresses the shift towards a low-carbon and digital economy as part of one single transition.

The high intensity of minerals and metals in the transition towards a low-carbon and digital economy implies that the world is moving from dependence on fossil fuels to dependence on multiple elements in the periodic table. Digital devices and hardware may contain dozens of minerals and metals, which are essential for their functioning and cannot be easily substituted. The amount of minerals and metals used in a device may be very small, particularly in view of the general trend towards miniaturization, which complicates recycling of these materials or metals once they become waste (chapter IV). However, as digitalization evolves, the larger volumes of minerals and metals needed to match global demands are accompanied by an increase in the variety of elements required at high degrees of purity; this is to allow for the higher complexity and continuously improved performance of devices. In the case of telephones, as illustrated in figure II.2, the number of elements used in telephones made in 1960 was 10, rising to 27 elements for telephones made in 1990. In 2021, a smartphone contained as many as 63 of the elements in the periodic table.

> Higher complexity and improved performance of devices require larger volumes and an increased variety of minerals and metals

Apart from being present in tiny amounts and in high numbers, minerals and metals are mixed in alloys, which makes separating for recycling and recovery purposes very difficult (chapter IV). Moreover, the high levels of purity needed are ensured through energy-intensive processing. Declining or low mineral concentration of the ores extracted also requires huge

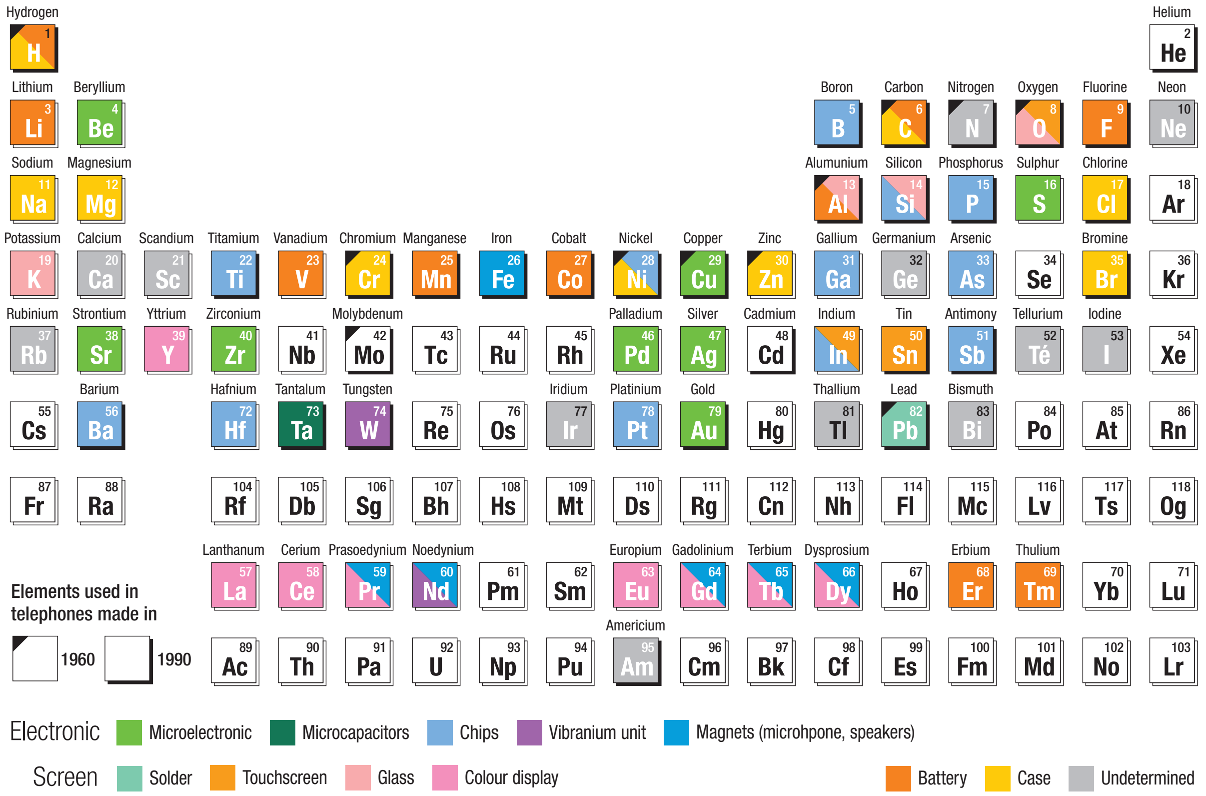
Figure II.1
Number of lists compiled by countries of critical minerals/raw materials which include a certain critical mineral/raw material, by technology



Source: UNCTAD, based on IRENA (2023) and Carrara et al. (2023).

[6] Based on a review of various studies of digitalization and natural resources, including Carrara et al. (2023); Dedryver (2020); Deutsche Bank (2022); Eerola et al. (2021); Ganier (2021); Global Electronics Council (2021); GSMA (2022a); Marscheider-Weidemann et al. (2021); Poinssot et al. (2022) and University of Birmingham et al. (2021); see also https://www.visualcapitalist.com/visualizing-the-critical-metals-in-a-smartphone/.

Figure II.2
Evolution of elements of the periodic table contained in a phone
Elements used in smartphones in 2021, by component



Source: Le Monde Diplomatique, What's in a phone? October 2021.

amounts of ore to derive the final mineral content needed for the devices.

On average, over the past four decades, ore grades have declined by half for many commodities (Morrill et al., 2022). A study by the non-governmental organization Justice et Paix (2019) notes that manufacturing a 2 kg computer involves the extraction of 800 kg of raw materials. Generally, manufacturing electronic devices requires 50 to 350 times of their final material weight. Similarly, Ganier (2021) points out that 70 kg of raw materials are needed to produce, use and eliminate one smartphone.[7] Overall, this implies that the more efficient a product may be in terms of its performance for digitalization purposes, the less efficient it becomes in terms of material use (Valero et al., 2021).

While minerals and metals are essential for digitalization even if used in tiny amounts, the influence of their use for digitalization in global markets varies. For some, their application for digital purposes represents a relatively lower share when compared to other uses or to the demand for minerals and metals. In some other cases, digitalization represents a major share of minerals and metals use (Pitron, 2021; Ericsson et al., 2020; Malmodin et al., 2018).

As the discussion in this chapter cannot cover all the minerals and metals used in digital technologies, a selection of elements

The more efficient a product may be in its performance for digitalization purposes, the less efficient it becomes in material use

[7] In a discussion about material input per service unit, which indicates the quantity of resources used for a product or service, Pitron (2021) and Ritthoff et al. (2002) note the high levels present in digital technologies. For instance, in the case of semiconductors, an integrated circuit of 2 g requires 32 kg of material, at a ratio of 16,000 to 1. Pitron also notes that the weight of a mobile telephone is not about 150 g but may reach 150 kg, see *Reporterre* (2021).

is considered, notably aluminium, cobalt, copper, gold, lithium, manganese, natural graphite, nickel, rare earth elements and silicon metal.[8] The selection can be considered as sufficiently representative to illustrate relevant points, as it includes elements from various parts of devices, as well as from different minerals-producing developing countries.

2. Digitalization trends contributing to increased demand for minerals and metals

The discussion in the previous section implies that rapid digitalization cannot take place without the significant use of physical raw materials, including minerals and metals. Several factors can influence increases in global minerals and metals demand, such as population and economic growth, as well as urbanization trends. The recent surge in mineral demand is mostly attributed to their use in low-carbon technologies, such as for renewable energies and electric vehicles (Hund et al., 2020; IEA, 2021a). According to IEA (2023a), as a result of increasing demand and prices, the market value for transition minerals doubled between 2017 and 2022.

Exponential growth in the demand for digital products and services is further accentuating the push for increased mineral extraction

However, exponential growth in the demand for digital devices and ICT infrastructure, as well as for computing power and data, is further accentuating the push for the increased extraction of minerals and metals (figure II.3).

This section provides some evidence of the evolution of Internet and data traffic, and discusses trends related to the demand for digital devices, hardware and equipment that enable connections; data transmission infrastructure; and dynamics in relation to data centres, which are essential for data storage, processing and use. While trends are presented with a broad time perspective, the focus is on the prospects for demand related to digital devices and hardware that could influence minerals and metals consumption in future. To the extent possible, trends are expressed in volume terms, as the environmental dimension is more closely associated with material aspects rather than with economic value.

a. Internet and data traffic

Internet traffic relates to the volume of different online activities, while data traffic encompasses the volume of exchanged data. UNCTAD (2019a, 2021a) has provided evidence of the surge in Internet and data traffic over the past couple of decades. Various industry sources suggest that these exponential trends are expected to continue, as follows:

- Reinsel et al. (2018) predicted that the global datasphere would grow from 33 zettabytes in 2018 to 175 zettabytes by 2025. Estimations by Burgener and Rydning (2022) project data to grow at a compound annual growth rate of 21.2 per cent between 2021 and 2026, to reach more than 221 zettabytes.[9]
- According to TeleGeography (2024a), the growth in international Internet bandwidth largely mirrors that of Internet traffic. Global Internet bandwidth has tripled from 2019, to reach 1,217 Tbps in 2023.[10]
- According to Ericsson (2023a),[11] global data traffic saw a fourfold increase from 2018 to 2023, when it reached 490 (EB) exabytes per month. Fixed data traffic represented about two thirds of overall data traffic, with mobile network traffic (i.e., mobile data and fixed wireless access

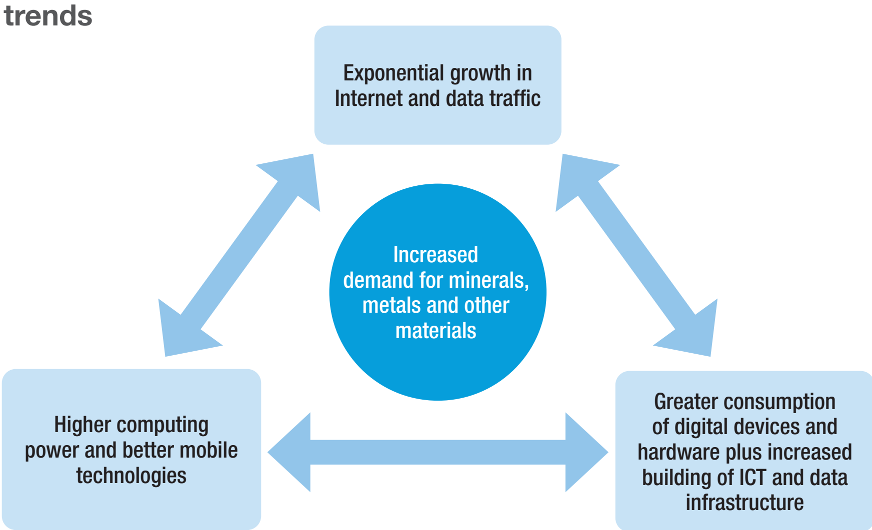
[8] The choice is based on a review of the studies on digitalization and natural resources cited in footnote 7.

[9] One zettabyte is equal to 1,000 exabytes.

[10] Tbps refers to Terabytes per second, i.e. 1,000 gigabytes per second.

[11] Total data traffic in this source includes mobile data, fixed wireless access and fixed data. Statistics on Internet and data traffic are often provided by private companies whose methodology is not standardized. It is therefore useful to look at more than one estimate. Nevertheless, all estimates show that the trend of rapidly increasing Internet and data traffic is likely to continue in future.

Figure II.3
Dynamics of increased material consumption and digitalization trends



Source: UNCTAD.

traffic) accounting for the remaining third. Global mobile network data traffic almost doubled in two years, to reach 160 EB/month in 2023 (Ericsson, 2022, 2023a).

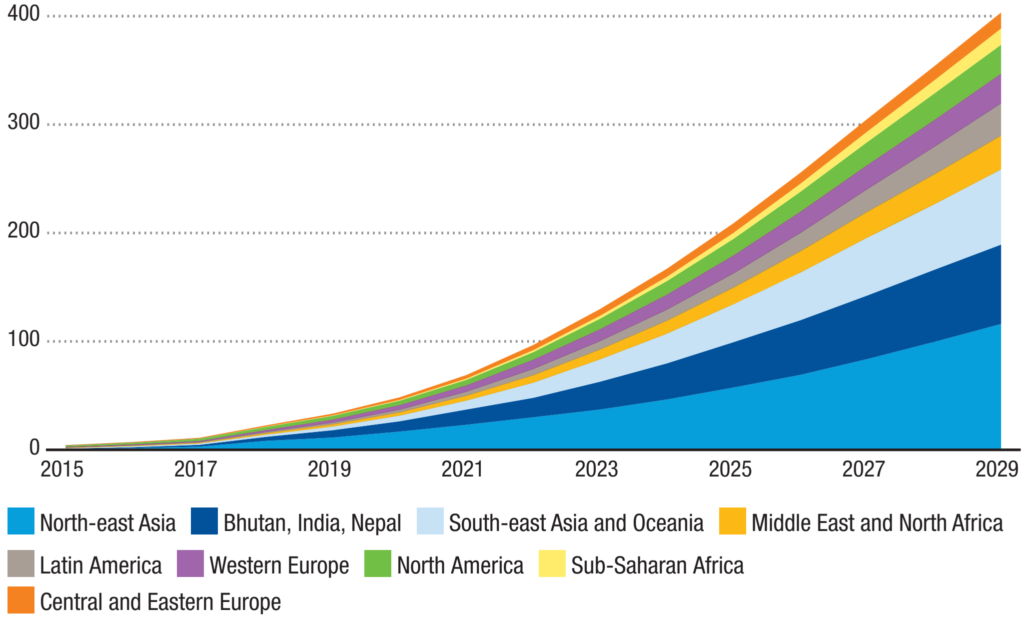
- Video traffic is estimated to account for almost three quarters of all mobile data traffic (73 per cent), mainly through smartphone use. Globally, growth in mobile data traffic per smartphone can be attributed to three main drivers, namely, improved device capabilities, an increase in data-intensive content and growth in data consumption due to continued improvements in the performance of deployed networks.
- Concerning future trends, the volume of global data traffic is forecast to grow by a factor of 2.5 by 2029, reaching 1,223 EB/month. By 2029, the share of fixed data traffic is expected to shrink to 54 per cent, as mobile network traffic will experience faster growth, reaching 46 per cent (Ericsson, 2023a).

In 2023, almost one third of global mobile data traffic was generated in Northeast Asia, followed by the group formed by Bhutan, India and Nepal (figure II.4).[12] In China, mobile data traffic accounted for more than the combined mobile data traffic of North America and Western Europe. In absolute terms, developing regions are forecast to drive the global increase in mobile data traffic in the period 2023–2029. Large markets at early stages of launching fifth-generation (5G) mobile networks are likely to further boost mobile traffic. Sub-Saharan Africa had the lowest mobile data traffic in 2023, but this region is forecast to experience the most dynamic growth in 2023–2029 (Ericsson, 2023a).

Much of the increase in Internet and data traffic will be enabled by improvements in mobile technologies. The commercial roll-out (infrastructure supply side) of 5G technologies that started at the end of the 2010s reached 280 networks globally in 2023, a notable increase from 228 in 2022. Access to 5G networks is expected to experience the most significant growth in the near future, with global population coverage rising from an estimated 45 per cent in 2023 to around 85 per cent by 2029 (Ericsson, 2022, 2023a).

[12] This grouping is provided in Ericsson (2023a). The large volume of data traffic in the latter group likely reflects mainly usage in India.

Figure II.4
Mobile data traffic by country grouping, 2015–2029
(Exabytes/month)



Source: UNCTAD, based on Ericsson (2023b).
Note: Country groupings are as defined in the source.

Demand for 5G technology, in terms of number of subscriptions, is set to remain strong in the future. In 2023, such mobile networks represented about one fifth of all subscriptions. They are forecast to become the dominant mobile access technology by subscription in 2028 (figure II.5.a). By the end of 2029, there may be over 5 billion 5G subscriptions globally, accounting for almost 60 per cent of all mobile subscriptions.[13] This expansion will be led by Northeast Asia, notably China, followed by India. By 2029, these will account for half of all worldwide 5G subscriptions (figure II.5.b).

The shift to 5G will be accompanied by an increased supply of 5G-compatible devices, such as smartphones.[14] Devices operating on 3G and 4G are not fit to use 5G infrastructure. Sharply escalating data traffic due to 5G technology, coupled with a growing number of devices connecting to the Internet, could counteract potential gains in power efficiency brought about by 5G.[15] Building 5G networks requires extensive new and upgraded physical infrastructure, with only a small number of companies globally being able to provide the necessary equipment (*Foreign Policy*, 2021). Higher speeds and capacity enabled by 5G technology may lead to rebound effects and even more demand for devices, particularly smartphones. According to one forecast, shipments of 5G smartphones, as a share of all shipped smartphones, could rise from 61 per cent in 2023 to 83 per cent by 2027.[16]

[13] A similar forecast is advanced in GSMA (2023b), which states that 5G connections will represent 54 per cent of all connections by 2030.

[14] In January 2022, 5G smartphone sales penetration was estimated to have surpassed 4G; see https://www.counterpointresearch.com/insights/global-5g-smartphone-sales-penetration-surpassed-4g-first-time-january-2022/.

[15] See https://www.ft.com/content/a679291a-0f93-48f2-aac8-8cc5b108c79b.

[16] See https://www.idc.com/getdoc.jsp?containerId=prUS51430223.

Figure II.5.a
Global mobile subscriptions, by technology, 2018–2029
(Millions)

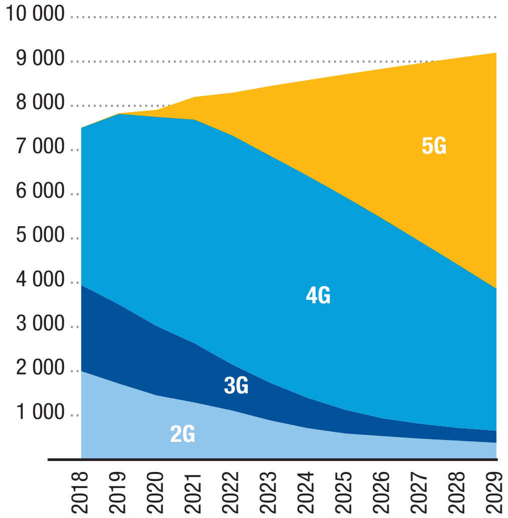
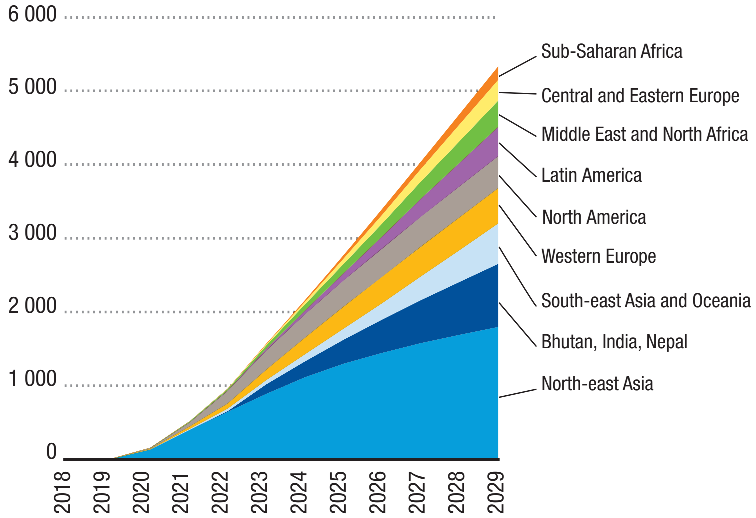


Figure II.5.b
Mobile 5G subscriptions, by country groupings, 2018–2029
(Millions)



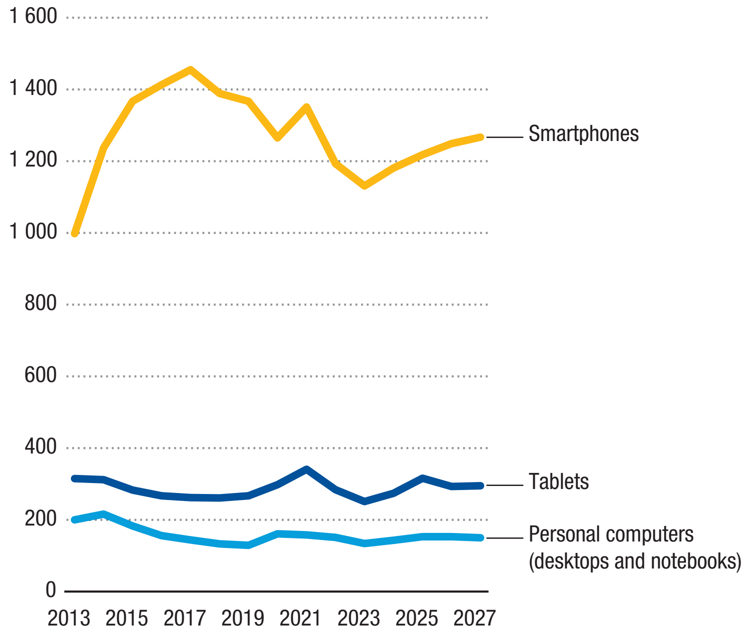
Source: UNCTAD, based on Ericsson (2023b).
Note: Country groupings are as defined in the source.

b. Devices and hardware for digital connections

The most popular digital devices over the past decade have been smartphones, personal computers and tablets, with smartphones accounting for the largest share (figure II.6). According to data provided by Canalys, global shipments of smartphones experienced robust growth from the beginning of the 2010s until 2017, when they peaked at nearly 1.5 billion units. Shipments then decreased until 2020, before bouncing back in 2021, linked to increased demand due to the pandemic. It is forecast that smartphone shipments will rebound in 2024 and reach almost 1.3 billion units by 2027.

The trend in personal computers (desktops and notebooks) has followed a different trajectory, declining until 2018 and then increasing, although recording a similar decline in 2022–2023. Worldwide tablet shipments also fell until 2019, followed by a rebound in 2020. Shipments of both

Figure II.6
Global shipments of selected digital devices, 2013–2027
(Millions of units)



Source: UNCTAD, based on data provided by Canalys.

personal computers and tablets are forecast to stay relatively flat between 2024–2027.[17]

An important growth area is seen in IoT devices, which include connected vehicles, machines, meters, sensors, point-of-sale terminals, consumer electronics and wearables.[18] It is estimated that about 39 billion connections will be related to IoT by 2029, compared to around 16 billion connections in 2023. As of 2021, such connections surpassed those of conventional devices (personal computer, tablet, mobile and fixed telephone), a trend which will strongly continue up to 2029.[19] The average number of IoT devices per capita will double from two in 2023 to more than four in 2029.[20] Other sources of data also show these increasing trends.[21] A forecast by GSMA Intelligence (Iji and Gurung, 2023), indicates that IoT connections will reach over 38 billion by 2030, with the enterprise segment accounting for more than 60 per cent of the total.

The regional distribution of cellular IoT connections reconfirms the dominance of North-east Asia (mainly China), with almost 70 per cent of the total in 2023 (figure II.7).

Demand for electric vehicles, which have become more like "computers on wheels" (Eisler, 2023), has become a leading factor in the increased consumption of minerals and metals.[22] It is estimated that electric vehicles use about six times more minerals than conventional vehicles (IEA, 2021b). According to estimations by IEA (2023b), sales of electric vehicles increased progressively during the 2010s, with 2 million units sold in 2018–2019, rising to 14 million in 2023.[23] Projected sales by 2030 are around at least 40 million.[24]

Apart from the demand generated by devices, trends in component sales are also linked to the demand for minerals and metals. Batteries and semiconductors, in particular, have been at the centre of supply chain bottlenecks in recent years. While there are different kinds of batteries, those used in electronic products are mostly lithium-ion batteries. In the 2000s, electronics were the primary drivers of demand for this kind of battery. This was maintained until the mid-2010s, when

[17] Estimations by IDC also point to a decrease of shipments between 2022 and 2023 for smartphones and personal computers reaching 1.17 billion and 259.5 million units, respectively. However, with the migration to 5G smartphones in emerging markets, as well as scheduled updates for personal computers, among other factors, it is forecasted that both smartphones and personal computer shipments will increase from 2024 onwards, to reach almost 1.3 billion and 285 million by 2027, respectively. IDC also forecasts the trend for tablet shipments as upward but more moderate, from 134 million units in 2023 to around 136 million units by 2027. See IDC (2024a) for personal computers, IDC (2023a, 2024b) for smartphones and IDC (2023a) for tablets.

[18] For example, global annual shipments of wearable devices are expected to increase from about 520 million units in 2023 to 625 million units in 2027 (IDC, 2023b); shipments of smart home devices are expected to rise from 860 million units in 2023 to 1.1 billion in 2027 (IDC, 2023c).

[19] UNCTAD, based on Ericsson (2023b).

[20] UNCTAD calculations, based on Ericsson (2023b) and the UNCTADstat database.

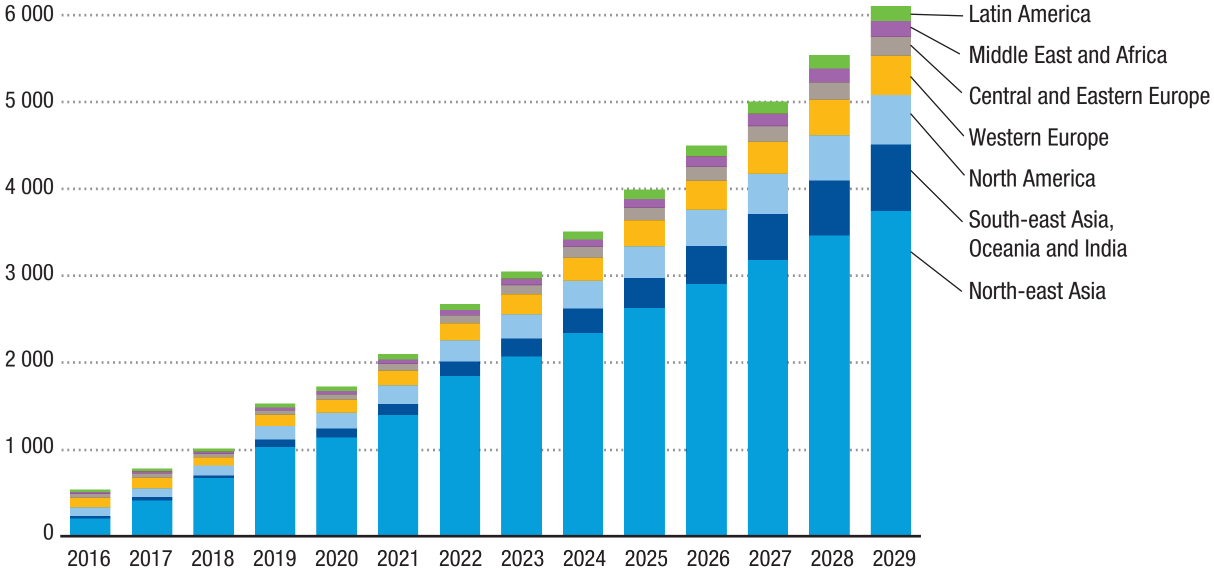
[21] IoT Analytics estimated that there were 14.4 billion IoT connections in 2022, forecast to reach over 29 billion in 2027 (see https://iot-analytics.com/number-connected-iot-devices/). In 2022, GSMA Intelligence forecast that the number of IoT connections (enterprise and consumer) would reach 37.4 billion globally by 2030, up from 15.1 billion in 2021; enterprise connections would be the main driver of growth, accounting for 76 per cent of the increase over the forecast period. Enterprise connections will surpass consumer connections in 2024 (Hatt et al., 2022).

[22] See footnote 3.

[23] The term electric vehicle is used to refer to both battery electric and plug-in hybrid electric vehicles (IEA, 2023b).

[24] China is the main market for electric vehicles, accounting for around 60 per cent of global sales. More than half of electric vehicles in the world are in China. Europe is the second largest market, and sales increased by over 15 per cent in 2022, with electric vehicles accounting for one in every five vehicles sold. Electric vehicle sales in the United States, the third largest market, increased by 55 per cent from 2021 to 2022, reaching a sales market share of 8 per cent.

Figure II.7
IoT devices with cellular connections, by country grouping, 2016–2029
(Millions of connections)



Source: UNCTAD, based on Ericsson (2023b).
Note: Country groupings are as provided in the source (2023 data are estimates).

demand for lithium-ion batteries increased exponentially due to the growing popularity of electric vehicles. In 2022, electronics accounted for about 13 per cent of total lithium-ion battery demand, of about 90 GWh/year (BloombergNEF, 2023a).[25]

When analysing the demand for batteries by application, Liu et al. (2022) show that in 2018, demand for consumer electronics was 20.5 per cent of the total, although this share is expected to decline to 2.6 per cent in 2030. Thus, although demand is still increasing,[26] it plays a minor role compared to the 88.9 per cent share for electric mobility. In geographic terms, in 2018, China accounted for 68.5 per cent of the total battery demand, a share that is set to drop to 42.8 per cent in 2030.

In order to match increasing demand, there are projects in place to substantially increase production by building battery gigafactories around the world. Benchmark Source (2023) estimates that by the end of 2023, there were over 240 gigafactories in operation across the world, with forecasts for over 400 by 2030. In 2023, 82 per cent of gigafactory capacity was located in China. It is anticipated that as a result of policies in some developed countries encouraging domestic production may lead to a drop to 68 per cent in 2030. By comparison, in May 2022, estimates for gigafactories in the pipeline reached 304, marking a significant increase from the number planned in September 2019, implying a tripling of the initial figure. China is expected to remain the dominant player for the next decade (Stichting Onderzoek Multinationale Ondernemingen (SOMO), 2023).[27] By late 2023, no plans for battery gigafactories were known to have been registered in

[25] Data based on BloombergNEF's web page for the presentation of the Electric Vehicle Outlook 2023, at https://about.bnef.com/electric-vehicle-outlook/ (accessed on 10 January 2024).

[26] Demand for consumer electronics would increase from 38 GWh in 2018 to 69 GWh in 2030 (see https://battery2030.eu/battery2030/about-us/impact-and-challenges/).

[27] On the increase in international investment in battery manufacturing projects, see also UNCTAD (2023d).

The per capita use of devices and connections illustrates the magnitude of the digital divide between developed and developing countries

Africa or Latin America, where a large majority of battery minerals are extracted.

Semiconductors are another important component of electronic devices that have been registering increasing demand and, notably, supply shortages. Semiconductor sales reached record levels in 2022 in terms of both value and units sold. Unit sales surged from about 25 billion in 2001 to nearly 100 billion in 2022. Global demand for semiconductor manufacturing capacity is projected to increase by 56 per cent by 2030.[28]

Beyond the absolute volumes of devices, the number of devices and connections per capita, as presented in figure II.8, illustrates the magnitude of the divide between North America and Western Europe, on the one hand, and developing regions such as Asia and Pacific, Latin America and the Middle East and Africa on the other.

Similarly, estimations by Baldé et al. (2024) of the global average number of per capita items in stock, by country income level, for the e-waste categories that refer more specifically to digitalization[29] show that in 2022, on average, ownership per capita was seven devices in high-income countries, 1.4 in upper middle-income countries, 0.7 in lower middle-income countries and 0.2 in low-income countries.

Additionally, trends in robotics are influencing demand for raw materials related to digitalization. Worldwide installations of industrial robots and professional service robots reached 553,000 and 158,000 units respectively, in 2022.[30] Over the previous decade, annual increases in industrial robots were registered, except in 2019 and 2020, due to the pandemic (International Federation of Robotics, 2023).

In 2022, seven out of ten industrial robots were installed in Asia and Oceania, followed by Europe and the Americas. China alone accounted for half of global industrial robot installations in 2022, up from 14 per cent in 2012. China was followed by Japan, the United States, the Republic of Korea and Germany; combined, these five countries reached almost 80 per cent of global installations in 2022. The electrical and electronics industry became the main user of industrial robots in 2020 (overtaking the automotive industry) and has maintained this position, reaching almost 157,000 units in 2022, accounting for more than one fourth of all robots (Müller, 2023a).

In terms of the operational stock of industrial robots (i.e. the accumulated number of robots in use), the installed base tripled between 2012 and 2022, from 1,235 to 3,904 thousand units (International Federation of Robotics, 2023). This is likely to grow in the future on the basis of increasing expectations of installations, which could reach 600,000 units per year worldwide by 2024 and 700,000 units in 2026 (Müller, 2023a).

c. Data transmission infrastructure

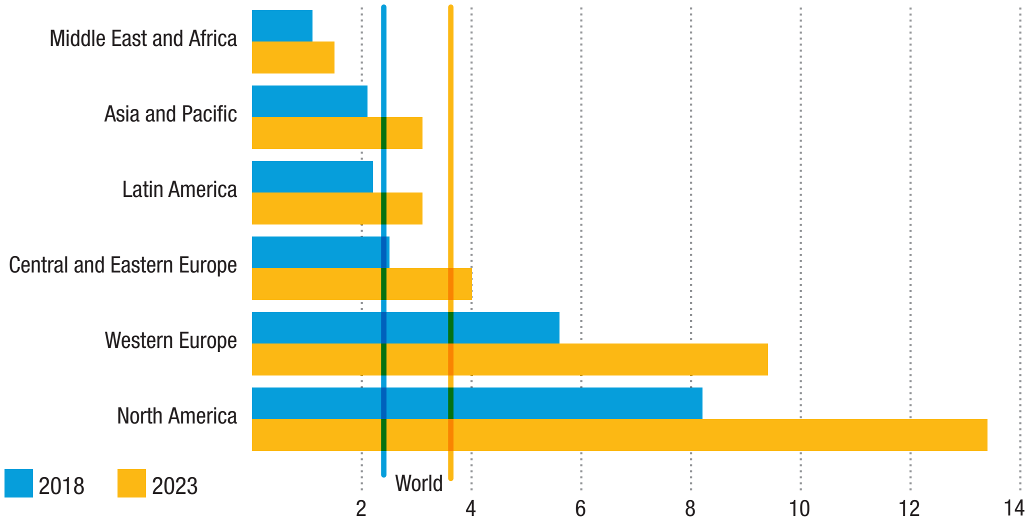
Most data flow through submarine cables. The total number of such cables worldwide is constantly changing, as older cables are decommissioned and new cables enter service. Nevertheless, the overall trend is upward. The number of submarine cables grew from 428 in 2017 to 574 active and planned cables in early 2021. During the same period, the combined length of such cables rose from 1.1 million to 1.4 million km (TeleGeography, 2017, 2021, 2024b). This

28 See https://www.semiconductors.org/despite-short-term-cyclical-downturn-global-semiconductor-markets-long-term-outlook-is-strong/.

29 This refers to screens and monitors, as well as small IT and telecommunications equipment. For a more detailed discussion on the e-waste categories used by UNITAR, see chapter IV.

30 Robots are as defined by the International Organization for Standardization and the following categories of products are non-robot ones: software (bots, AI, robotic process automation), remote-controlled drones, voice assistants, autonomous cars, automated teller machines, smart washing machines. Consumer (as opposed to professional) service robots reached 5 million units in 2022 (International Federation of Robotics, 2023).

Figure II.8
Average number of devices and connections per capita, by region, 2018 and 2023



Source: UNCTAD, based on Cisco (2020).
Note: Country groupings are as defined in the source.

trend is expected to continue until 2025, reaching nearly 1.6 million km, then declining to around 1.4 million km in 2028–2032, before rising again to 1.6 million km in 2035 (Stronge and Mauldin, 2023).

Online content providers (such as Google, Facebook, Microsoft and Amazon) are now the major investors in new submarine cables. In recent years, the capacity deployed by private network operators has outpaced Internet backbone operators. Faced with the prospect of ongoing massive bandwidth growth, owning new submarine cables allows these users to have greater control of data flows (TeleGeography, 2021). Moreover, these companies can lay several cables along the same route, for security reasons and to prevent any slowdown in activity.[31]

Cables are engineered with a minimum design life of 25 years, although they may remain operational for longer. They may also be retired earlier, as cables become economically obsolete when they cannot provide as much capacity as newer cables at a comparable cost. It is expected that requirements for new cables will continuously increase from 2023; in 2035, half of the 1.6 million km of cables are likely to be newly built (Stronge and Mauldin, 2023).

Besides submarine cables, satellites also play a growing role in Internet traffic and data transfers, particularly for remote locations. As of April 2023, there were 7,560 operating satellites in space, a sharp increase by more than 2,000 units compared to the same period in 2022 (5,465 units). Almost 7 out of 10 satellite operators or owners were from the United States, followed by China, with 1 out of 10. The emergence of companies such as SpaceX and One Web, which operate low Earth orbit satellites to provide broadband Internet from space, has contributed to a sharp increase in the number of annual satellite launches. About 80 per cent of all operating satellites were launched in the period from 2019 to April 2023, with SpaceX accounting for more than half of all operating

[31] See https://usbeketrica.com/fr/article/la-moitie-de-la-capacite-des-cables-mondiaux-est-aujourd-hui-utilisee-par-les-gafam.

satellites. In terms of use, 80 per cent (6,081 units) were commercial satellites, focussing mainly on communications.[32]

The extraordinary changes under way in outer space are expected to continue, with implications for sustainability, safety and security, as well as present and future governance (United Nations, 2023a).

d. Infrastructure for data storage, processing and use

Data centres are spaces where data are stored and processed. These facilities require huge computing capacity. While the relationship between data centres and the environment is mostly seen in terms of energy and water use (see chapter III), they also have a major impact on material demand through their use of computers and servers (Hoosain et al., 2023). The environmental sustainability of data centres needs to be assessed from a holistic perspective over their life cycles; decisions to frequently replace equipment to respond to energy efficiency requirements may lead to higher material consumption (Laurent and Dal Maso, 2020).

Frequently replacing equipment to respond to energy efficiency requirements may lead to higher material consumption

According to the Data Center Map, between January 2021 and January 2024, the number of co-location data centres increased from 4,714 to 5,522. The growth rate of installations was higher in developing economies (22 per cent) than in developed economies (16 per cent) in the same period. Still, more than 80 per cent of all data centres were located in developed countries as of January 2024.[33]

In addition to their increasing numbers, data centres have been evolving to meet the latest IT advancements and demand for compute-intensive workloads (cloud services, AI, machine learning, IoT, blockchain and cryptocurrencies, 5G networks, edge computing). These technologies require high processing power and high-density racks[34] that go beyond the traditional 2 to 5 kW. As a result, enterprise and on-premises data centres are increasing average rack density, a concern that was once unique to high-performance computing servers and hyperscale centres.[35] Increasing rack density means that more power and cooling capacity can be delivered for each server rack, which allows for more IT equipment to be hosted. For instance, a survey of data centres showed that average rack density had increased from 5 to 7.8 kW between 2018 and 2021 (Kleyman, 2021).

Data centres have also responded to demand for services by increasing the space of their facilities. For instance, while the number of hyperscale data centres has been growing rapidly, their total capacity has been growing even more quickly.[36] From 2016 to 2021, the number of hyperscale data centres doubled to 700 facilities worldwide, but it took less than four years (2017–2021) for their capacity to double. In 2022, there were already more than 800 hyperscale data centres, with the United States accounting for 53 per cent of their combined capacity, followed by Europe (16 per cent) and China (15 per cent). By mid-2023, the number of hyperscale data centres in operation was estimated to be 926, with a further 427 facilities in the pipeline. Meanwhile, the

[32] UNCTAD calculations, based on data from https://www.ucsusa.org/resources/satellite-database (accessed on 30 March 2023).

[33] UNCTAD calculations, based on https://www.datacentermap.com/datacenters.html. Available data are based on entries primarily added and maintained by service providers. The database only includes countries with at least one or more data centre; if a country does not appear, this indicates that the country does not have a data centre or that data are not available.

[34] Rack density is the amount of power the equipment uses in a server rack, measured in rack density in kilowatts (kW) per cabinet and used as a factor in data centre design (particularly for capacity and cooling/power planning). For more details, see Azap (2022).

[35] For a more detailed discussion, see Velimirovic (2021).

[36] Capacity is measured by critical IT load, which is the portion of electric power capacity, in megawatts, reserved solely for owners or tenants of a data centre to operate computer server equipment. The term does not include any ancillary load for cooling, lighting, common areas or other equipment. See Law Insider (2023).

average IT load of individual data centres is being ramped up and there is a likelihood of retrofitting existing data centres to boost capacity. The overall result is that the total capacity of all operational hyperscale data centres is expected to grow almost threefold between 2023 and 2029 (Synergy Research Group, 2021, 2022, 2023).

The surge in hardware and capacity in data centres is also the result of the increasing need to process data for use in new AI models. As these models grow and require more computing power and hardware to train the data, the environmental cost in terms of use of materials increases accordingly (Crawford, 2021).[37]

Taken together, the demand for digital devices and ICT and data infrastructure at all stages of the data value chain is set to remain strong over the next decade. Most of the demand for and the production of digital devices, data and ICT infrastructure is led by developed countries and Asia, particularly China, with limited contributions by Latin American and African countries. The dominance of a few large companies from the United States and China continues to increase (Moriniere, 2023; UNCTAD, 2021a).[38] These divides in terms of the demand and production of digital devices and hardware, as well as of digital infrastructure, suggest that developed countries and China together account for the majority of digitalization-related consumption of global minerals and metals. In contrast, other developing countries, particularly in Africa and Latin America, contribute much less.

Developed countries and China account for most digitalization-related consumption of global minerals and metals, while other developing countries contribute much less

C. Demand projections and supply responses for transition minerals

1. Demand projections

Assessing future demand for minerals involves exploring potential scenarios that humanity may face in the coming decades. Numerous agencies and organizations have developed models to forecast such future scenarios. Until recently, most did not thoroughly consider the implications of mineral consumption stemming from the digital technologies they incorporated. However, concerns about the high demand for minerals for the technologies essential for the low-carbon transition have been noted. As emphasized above, digitalization relies largely on the same minerals. Two of the most prominent reports in the context of low-carbon technologies are from the World Bank (Hund et al., 2020) and IEA (2021a).

The study from the World Bank confirms that regardless of the chosen pathway to lower carbon emissions, the overall demand for minerals will inevitably increase significantly. Total anticipated minerals demand by 2050 varies from 1.8 billion to 3.5 billion tons, with the most ambitious scenario reflecting a fourfold increase compared to 2020 levels. To meet the growing demand for low-carbon technologies, production of minerals such as graphite, lithium and cobalt could increase by nearly 500 per cent by 2050.

Given the crucial role of mineral consumption, IEA (2023a) estimates the

[37] Researchers measure the size of these models in terms of hundreds of billions of parameters, which are the internal connections used to learn patterns based on training data. For large language models such as ChatGPT, there was an increase from around 100 million parameters in 2018 to 500 billion in 2023 (Luccioni, 2023).

[38] See https://ecfr.eu/special/power-atlas/technology/.

amount of the primary minerals required for the updated scenarios explored in the global energy and climate model of 2022 (figure II.9). The scenarios include the stated policies scenario and the net zero emissions scenario by 2050, and these are consistent with limiting the global temperature increase to 1.5°C. Consumption of each mineral is projected to increase substantially (except for silver), with platinum-group metals as the most prominent case, reaching almost 120 times the consumption level of 2022 under the second scenario. In addition, under this scenario, by 2050, low-carbon technologies could account for 40–50 per cent of the demand for copper and neodymium (a rare earth element), 50–60 per cent of the demand for nickel and cobalt and up to 90 per cent of the demand for lithium.[39]

The global response to surging demand for transition minerals mainly seems to centre on increasing minerals extraction

Low-carbon technologies have rapidly emerged as the segment with the fastest growth in demand for transition minerals. A comparison of 11 reports providing critical minerals outlooks concurs on the increasing demand for minerals and their central role in the low-carbon transition (International Energy Forum and The Payne Institute for Public Policy at the Colorado School of Mines, 2023). However, these demand projections show large variations based on the different types of scenarios chosen, the mix of technologies deployed, assumptions about resource intensity, technology developments and recycling rates. Moreover, the focus of these models on the low-carbon or clean energy transition scenarios may lead to underestimations; demand for conventional purposes, reflecting usual growth and development trends, as well as for digitalization, may not be properly factored in. Overall, the share of increased demand for transition minerals that can be attributed to digitalization is not known.

2. Supply response in view of the limitations of a finite planet

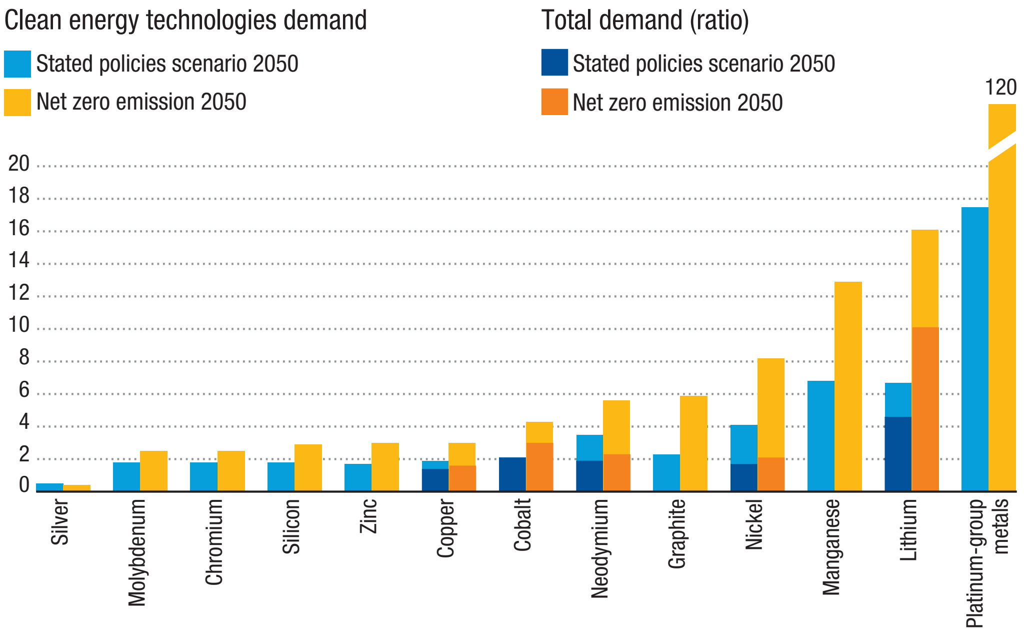
The global response to surging demand for transition minerals mainly seems to centre on increasing minerals extraction. Importing countries aim to secure access to these minerals, often by ramping up domestic mining operations (section D.4), as part of widespread efforts to bridge the gaps between supply and demand in the mining sector. For example, global exploration budgets rose by 16 per cent in 2022, following a strong 34 per cent rebound in 2021. Latin America was the primary destination of 25 per cent of this exploration in 2022, while Africa was second, accounting for 17 per cent (S&P Global Market Intelligence, 2023). Investment in critical minerals development rose sharply, by 30 per cent in 2022, following a 20 per cent increase in 2021 (IEA, 2023a). It remains to be seen whether this investment will be enough to meet increasing demand.

Besides the push to extract more mineral resources around the world, and possibly reflecting concerns about the cost of extracting the anticipated volumes needed, there is interest in expanding the mining frontier beyond land-based territories. Growing demand for transition minerals, and the associated more exploration and extraction activity in mines on land is prompting actions towards expanding the mining frontier into uncharted areas. This includes mining in the deep sea and in space (box II.1).

Supply responses to the surging demand for transition minerals may lead to time lags and supply deficits in the short to medium term. This is because it takes several

[39] UNCTAD, based on IEA (2023c).

Figure II.9
Projected increase in mineral demand by 2050
(Ratio of 2050 to 2022 consumption)



Source: UNCTAD, based on IEA (2023c).
Note: The figure shows minerals demand estimates for clean energy technologies for all minerals. Total demand estimates are provided by IEA only for copper, cobalt, lithium, nickel and neodymium

years between investing in exploration, developing mines and actual mineral production. However, a crucial question, from both an economic perspective and from an environmental and geological perspective, is whether there will be sufficient minerals to meet the huge needs for low-carbon and digital technologies.

As the world becomes more dependent on minerals that form the basis such technologies, the supply faces increasing pressures and extraction difficulties. Paradoxically, this could eventually become an obstacle to developing such technologies, as minerals could become increasingly costly to extract. Moreover, beyond the international inequalities related to mining, this could create intergenerational inequality. The overall conclusion of the potential limits to minerals supply on a finite planet, resulting from exponential demand and growth trends, is the need to rethink the use of transition minerals and move towards more responsible and sustainable modes of both consumption and production.

Most of the analyses of supply risk in the context of different criticality assessments for minerals and metals in many countries focus on the risks in producing countries, with an emphasis on geopolitical factors (see section D). Moreover, some optimistic views on the future availability of minerals resources tend to look at short to medium term behaviours and evolution, considering that the Earth has yet to be fully explored. However, these tend to neglect important physical geology aspects, including the technology required for extraction and the environmental, social and economic impacts that extreme mining could entail. All of these considerations are critical for making realistic assessments in this context. The annex to chapter II explores concerns about mineral depletion.

A crucial question is whether there will be sufficient minerals to meet the huge needs for low-carbon and digital technologies

Box II.1
Is the expansion of the mining frontier sustainable?

In recent years, technological advances have made exploration in the deep sea and in space more feasible, and possible at relatively lower costs, which could lead to commercial mining in the near future. However, there is high uncertainty about the economic, social and environmental implications, as well as a lack of clarity about the international regulatory regimes that would apply. Notably, as both the deep sea and space are global commons, a key issue that needs to be clarified is the equitable sharing of benefits from the minerals extracted. The race for exploration and mining in the deep sea and in space is ongoing among major players with the expertise and necessary resources.

The 1982 United Nations Convention on the Law of the Sea restricted mining in the sea outside special "exclusive economic zones", i.e. the 200 nautical miles from the shores of countries. According to one of its provisions, if a country, collaborating with a mining company, applied to start deep sea mining, the International Seabed Authority (ISA), set up in 1994, had two years to finalize regulations or mining could commence. Nauru and the Metals Company made an application in June 2021, implying that if an agreement on new rules was not reached by July 2023, mining could start. By mid-2023, ISA had issued 31 exploration licences. Following negotiations, the Council of ISA was not able to finalize the regulations under the two-year rule, yet noted the intention to continue the elaboration of rules, regulations and procedures, with a view to their adoption at the thirtieth session of the Council in 2025.

The debate on the commercial exploitation of mineral resources from the deep sea has intensified in recent years. Those in favour point to the contribution to the necessary supply of minerals for low-carbon and digital technologies, as well as to unsustainable practices in land mining. By contrast, those against deep sea mining point to the need to protect the oceans, which may face significant environmental damage, and the need to increase research on little-known deep-sea ecosystems, before authorizing any extractive activity. One example is the exploitation of the Arctic. As the ice melts in this region due to the effects of climate change, mining activities could become more feasible, but with high costs for the environment and for communities, particularly indigenous communities whose livelihood and existence depends on Arctic ecosystems. In this context, there have been calls from a number of countries, the private sector, civil society and the scientific community in particular, to halt deep-sea mining, through a ban, moratorium or a precautionary pause.

Similar concerns arise from the race for mining in outer space, which relates to mining the resources of celestial bodies such as the moon, planets and asteroids, based on their significant economic potential. While there is ongoing review within the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), there is no agreed international framework on space resource exploration, exploitation and utilization, nor a mechanism to support its future implementation. Without agreed international principles on such activities, these economic incentives may carry a potential risk of conflict, environmental degradation and cultural loss. When related space treaties were negotiated, provisions were included to ensure that no nation could claim ownership of celestial bodies, recognizing the common interest of all humankind in the progress of the exploration and use of outer space for peaceful purposes. Some Governments have contended that the exploitation of space resources is permissible, including by private sector actors.

In sum, the expansion of the mining frontier towards the deep sea or outer space raises many questions. Before moving to commercial mining activities, it would be wise to allocate sufficient time to properly assess the related benefits and costs for inclusive and sustainable development. Moreover, the international community should work further to establish the proper international regulatory regimes, including on equitable benefit sharing. In 2021, the COPUOS began to collect information on space resource activities and to study existing legal frameworks, to develop a set of initial recommended principles, taking into account the need to ensure that any such activities are carried out in accordance with international law and in a safe, sustainable, rational and peaceful manner. This research is expected to be completed by 2027.

Source: UNCTAD, based on UNEP Finance Initiative (2022); IISD (2023); Standing (2023) for deep sea mining; and United Nations (2023a) for space mining.

D. Geopolitics and the dynamics of transition mineral markets

As transition minerals have become key inputs for both low-carbon and digital technologies, the importance of geopolitics, geoeconomics and geostrategic factors associated with their production, trade and access by different countries has intensified.[40] Transition minerals have become a major issue of concern on the international development agenda and are strongly interconnected with global challenges related to digitalization and environmental sustainability.

Increasing demand has been compounded by supply shortages linked to the pandemic and the war in Ukraine, leading to concerns about the availability of transition minerals globally. Moreover, transition minerals have become an additional factor in global trade and technology-related tensions, particularly among the leading actors in the digital economy.[41] Rivalry for resources is highlighted as "a potential cluster of interrelated environmental, geopolitical and socioeconomic risks relating to the supply of and demand for natural resources" that are contributing to the polycrisis of the current global context (WEF, 2023: 57).

This is reflected in the competition among various countries for securing access to transition minerals that are essential for sustainable technological, industrial, and economic progress. In this context, this section reviews the situation regarding global production, prices and international trade in transition minerals, as well as the different approaches towards dependence and supplier diversification taken by countries that import and those that export transition minerals.

1. Geographical concentration of reserves, extraction and processing

On the production side, the international market for transition minerals is characterized by high geographical concentration of mineral reserves, extraction and processing. Essentially, geography determines where mineral reserves and extraction are located. A large proportion of global extraction takes place in developing countries within Africa, Asia and Latin America; however, it is unevenly distributed between and within these regions.

In 2023, three countries in Africa had the largest global reserves of three transition minerals, as follows: the Democratic Republic of the Congo, with 55 per cent of global reserves of cobalt; Guinea, with 25 per cent of the global reserves of bauxite, used in aluminium production; and South Africa, with 32 per cent of global reserves of manganese. The latter country also held 9 per cent of global gold reserves. Madagascar, Mozambique and the United Republic of Tanzania together represented 24 per cent of global reserves of natural graphite.[42]

In Latin America, Chile and Peru led in terms of copper reserves. Together with Mexico, they accounted for 36 per cent of the total. The region also includes the "lithium triangle" which includes Argentina, the Plurinational State of Bolivia and Chile, with reserves of lithium accounting for

Transition minerals have become a major concern on the international development agenda contributing to global trade and technology tensions

[40] See IRENA (2023); Lazard (2023); Nakano (2021) and Wu and Huy (2022).

[41] See, for example, Byamungu (2022), who notes a "race" for minerals, and other studies that use more confrontational terms, such as Fabry (2023); Gibson and Zhou (2023) and Pitron (2019).

[42] UNCTAD calculations, based on https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries.

46 per cent of the world total.[43] Brazil has diverse and large reserves of transition minerals, including 26 per cent of natural graphite, 19 per cent of rare earth elements, 14 per cent of manganese, 12 per cent of nickel and 9 per cent of bauxite.

In Asia, Indonesia holds 42 per cent of global nickel reserves. China accounts for 40 per cent of global reserves of rare earth elements, 28 per cent of reserves of natural graphite and 15 per cent of reserves of manganese. Viet Nam holds 19 per cent of bauxite reserves and 20 per cent of rare earth element reserves.

Among the developed countries, Australia holds large shares of reserves for manganese (26 per cent), lithium (22 per cent), gold (20 per cent), nickel (19 per cent), cobalt (15 per cent), bauxite (11 per cent) and copper (10 per cent). The Russian Federation holds 9 per cent of rare earth element reserves and 19 per cent of gold reserves.

The concentration of transition minerals extraction, or mine production, is even higher, as shown in figure II.10. Minerals extraction increased significantly between 2010 and 2023 in response to surging demand. For cobalt, the Democratic Republic of the Congo accounted for 74 per cent of worldwide production in 2023; for lithium, Australia and Chile together represented 72 per cent of global production; and for manganese, Gabon and South Africa accounted for 59 per cent of total extraction. Indonesia represented 50 per cent of world nickel extraction. China accounted for 77 per cent and 69 per cent respectively of the world production of natural graphite and rare earth elements in 2023, and for 80 per cent of silicon metal production in 2022.

While the concentration of extraction is fundamentally determined by the location of minerals deposits, this does not necessarily translate into geographical control of the production of a mineral by the host country. Much production is undertaken by multinational enterprises that invest in the country (Leruth et al., 2022).

As can be seen in Figure II.11, the position of China is pronounced at the minerals processing stage and, with regard to some minerals such as nickel and cobalt, mining has intensified since 2019 (IEA, 2023a). China accounts for over 50 per cent of processing for aluminium, cobalt and lithium, about 90 per cent of processing for manganese and rare earth elements and close to 100 per cent of processing for natural graphite.

The leading role of China in minerals processing is the result of a combination of factors, including robust economic growth, substantial investments in infrastructure and technology, government strategies[44] and a trend among developed countries to outsource manufacturing to China. As Asia, particularly China, has emerged as a global electronics manufacturing hub, proximity to markets of intermediary products or components has also bolstered burgeoning minerals processing activities. The prominent position of China in minerals processing provides both economic and strategic benefits to the country. This has raised concerns in some major economies about dependence on mineral imports.

2. Evolution of prices

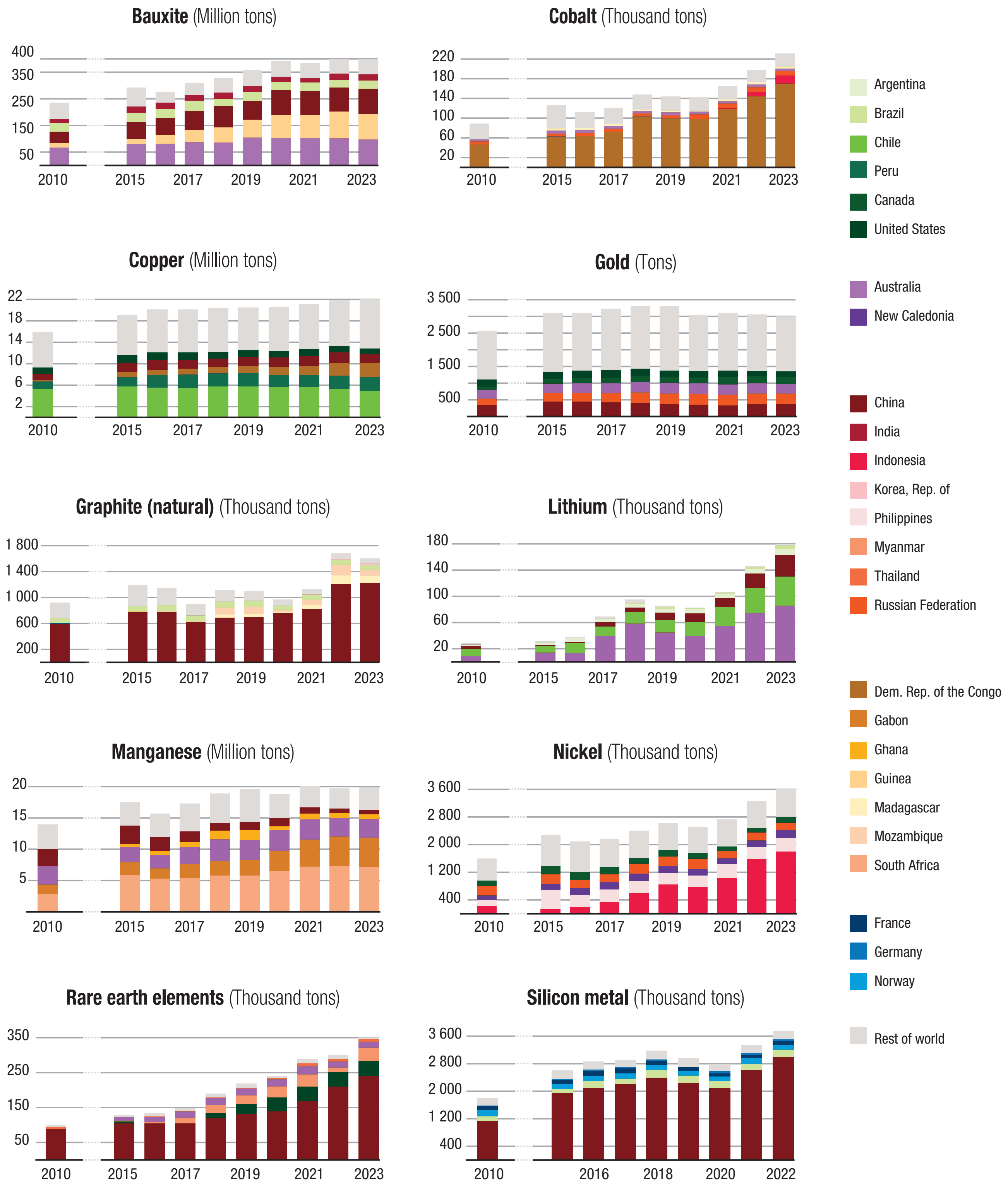
Due to the nature of supply and demand in this sector, minerals and metals prices are inherently volatile. This volatility has been particularly high for transition minerals in recent years, as shown in figure II.12.

In terms of trends, in response to surging demand and lagging supply responses, prices have generally increased. This is especially the case for lithium, nickel and rare earth elements (figure II.12). Many transition mineral prices remain above historical averages (IEA, 2023a). According to Standard and Poor's (S&P) (2024), by early 2024, prices for most metals are down 20 to 30 per cent from record highs in

[43] Data from the United States Geological Survey do not include the Plurinational State of Bolivia, which has the largest lithium reserves in the world (see https://qz.com/bolivias-lithium-reserves-are-even-larger-than-it-previ-1850664027).

[44] See Müller (2023b).

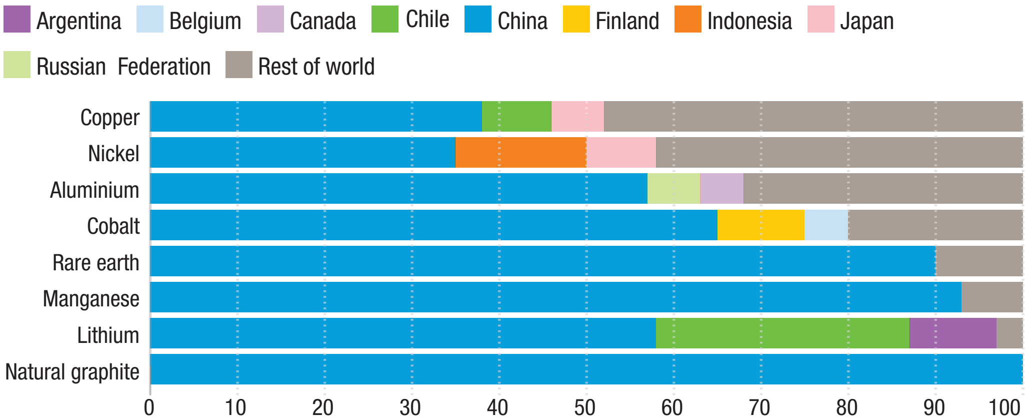
Figure II.10
Extraction of selected transition minerals by volume, selected economies and years



Source: UNCTAD, based on data from the United States Geological Survey.

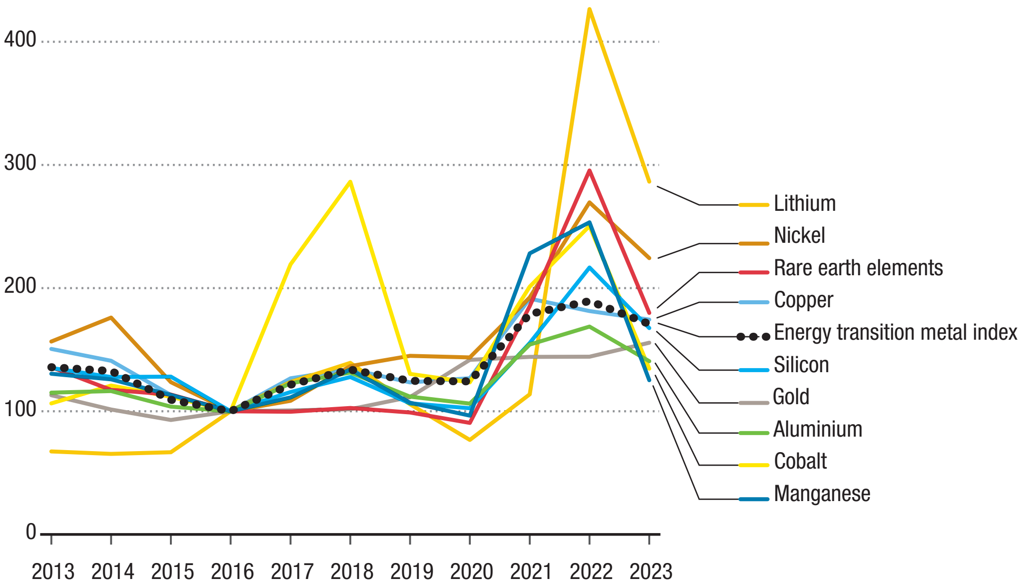
2021–2022, but are still about 20 per cent higher than before 2020. Overall, the outlook is that prices will continue on a rising trend, as demand increases rapidly and supply growth lags behind, in a context of fewer discoveries and lower ore grades. Against this background, significant structural supply bottlenecks can be anticipated in the coming decades, leading to higher prices.[45]

Figure II.11
Share of top mineral processing countries in world total for selected minerals
(Percentage)



Source: UNCTAD, based on OECD (2023a).
Note: The geographical concentration refers to 2021 for rare earth elements and to 2019 for all other minerals.

Figure II.12
Evolution of prices of selected transition minerals, 2013–2023
(Index, 2016 = 100)



Source: UNCTAD, based on IMF Primary Commodity Price System (9 February 2024 update), available at https://www.imf.org/en/Research/commodity-prices.

[45] See also https://www.policycenter.ma/publications/beyond-energy-crossroads-deciphering-key-trends-and-charting-path-2024; and Deutsche Bank Research (2023).

3. International trade of transition minerals along the global electronics value chain

a. International trade

International trade in transition minerals largely mirrors the geographical distribution of reserves and extraction presented above. Many developing countries in Africa, Asia and Pacific and Latin America are major exporters of mostly unprocessed minerals and metals for further processing, largely destined for developed countries and China. China, the United States and the European Union cannot meet their total mineral demand through domestic mining.

Refined minerals and metals go into the manufacturing supply chain to produce the various intermediary components that are assembled into final products. Over the past two decades, there have been significant regional shifts in the trade in metal raw materials. China has become the largest importer and exporter in the world, mostly importing ores and minerals and mainly exporting refined products and goods derived from them. By contrast, various developed countries such as the United States, as well as the European Union, have lost market shares (Perger, 2022).

Analysis by UNCTAD, in *The State of Commodity Dependence 2023*, shows that, in 2019–2021, the dominant commodity group in total merchandise exports among 31 countries was minerals, ores and metals, with several countries in Africa, Asia and Latin America showing an export dependence of more than 40 per cent on this commodity group in total merchandise exports. Australia is the only developed country that stands out among these exports (figure II.13). Burkina Faso, Mali and Suriname depend on gold for 80 per cent or more of their merchandise exports, and in Zambia and the Democratic Republic of the Congo, copper exports account for 69 and 53 per cent of total merchandise exports, respectively (UNCTAD, 2023e). By contrast, some developing countries with more diversified export economies also play a major role in international trade for different transition minerals. This is the case in Brazil for several transition minerals and in Indonesia for nickel.

Many developing countries are major exporters of mostly unprocessed minerals and metals, largely destined for developed countries and China

Countries can be classified by position in terms of international trade as importers or exporters of transition minerals (using the 10 minerals selected for use in this chapter for analytical purposes) and according to level of development, as presented in figure II.14.[46] The figure categorizes economies into mainly exporters or importers of transition minerals, although they may export and import different minerals. The European Union has an import reliance of 81 per cent for cobalt, 100 per cent for processed lithium, 96 per cent for manganese, 99 per cent for natural graphite, 75 per cent for nickel, 64 per cent for silicon metal and 100 per cent for processed rare earth elements.[47] The United States has set import reliance records for minerals, as it was more than 50 per cent reliant on 51 minerals in 2023, up from 47 in 2022. It is also 100 per cent net import reliant for 15 of those 51 minerals, 12 of which are deemed "critical".[48] Among developing countries, India is 100 per cent reliant on imports of, for example, lithium, cobalt and nickel, among other transition minerals (India, Ministry of Mines, 2023).

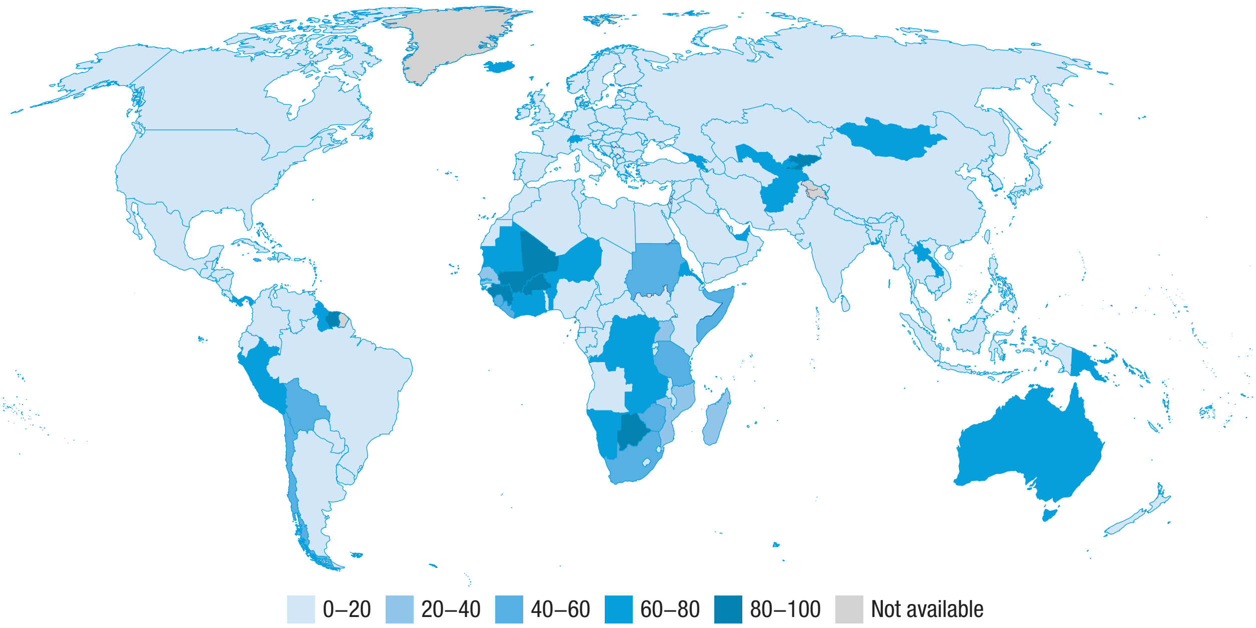
The above analysis is based on the value of trade, which has an impact on economic development. In order to consider the environmental aspects, it is also necessary to look at trade volume. The

46 This figure is not comprehensive, as it presents major exporters and importers in a representative manner. For more detailed analysis of international trade in critical minerals, including more countries and minerals, see https://www.trademap.org/Index.aspx, https://www.compareyourcountry.org/trade-in-raw-materials/en/2/BAUXI/all/default, https://resourcetrade.earth/ and https://oec.world/.

47 See European Commission, Directorate General for Internal Market, Industry, Entrepreneurship and SMEs et al. (2023).

48 See https://mineralsmakelife.org/blog/u-s-sets-mineral-import-reliance-record and United States Geological Survey (2023).

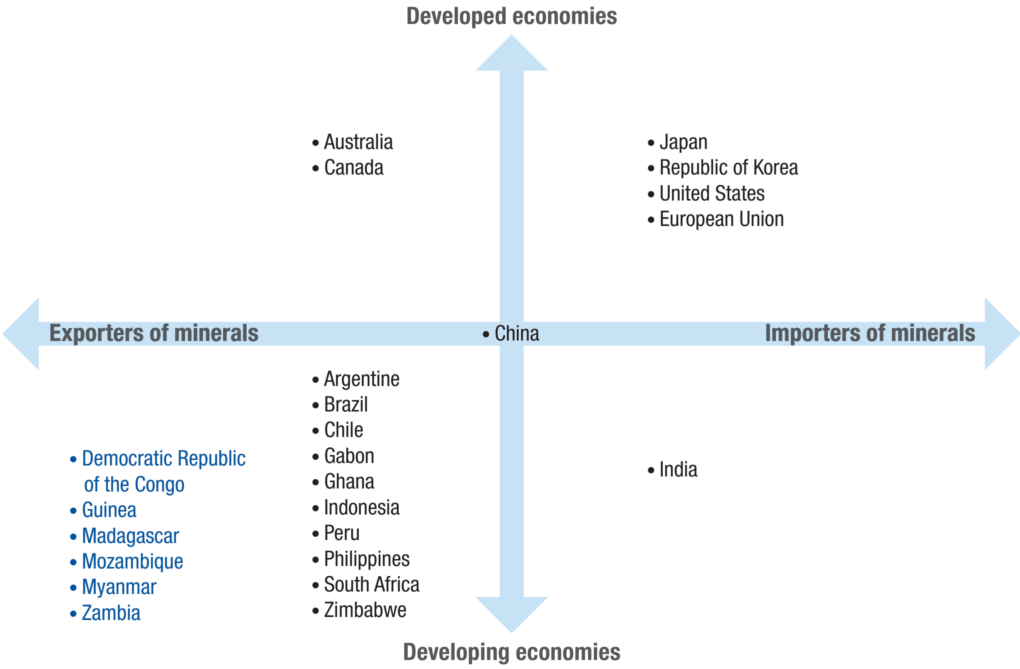
Figure II.13
Share of minerals, ores and metals in total merchandise exports, 2019–2021
(Percentage)



Disclaimer: the boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Source: UNCTAD (2023e).

Figure II.14
Classification of economies as exporters or importers of transition minerals, by level of development



Source: UNCTAD, based on data from the United Nations Comtrade database and UNCTAD (2023e).

Note: Countries in blue are LDCs.

volume of trade over the past half century has increased faster than the volume of extracted resources, which implies the growing dependence of the global economy on materials trade. The analysis of the material footprint of trade by UNEP and IRP (2020a), includes metals, ores and non-metallic minerals (in addition to biomass and fossil fuels), and highlights that resource-intensive processes have shifted from high-income importing countries to low-income exporting countries. This has been associated with a shift in environmental burdens towards the latter and is also relevant in the context of digitalization.

This dynamic is known as the "unequal ecological exchange" whereby activities with a higher value, which mostly include services and intangibles, are concentrated in developed economies.[49] Higher-income economies import resources and materials, yet outsource the material- and energy-intensive stages of production to other countries, while also externalizing the production-related environmental impacts to middle- and low-income countries. Developing countries therefore mostly export unprocessed and low-value minerals and metals and bear the environmental and social costs, and then have to import higher-value final products. In 2017, each person in the high-income group was dependent on the mobilization of an average of 9.8 tons of material resources in other parts of the world, with this reliance on external materials rising at a rate of 1.6 per cent per year since 2000 (UNEP and IRP, 2019). This cycle tends to self-perpetuate in a vicious circle unless it is actively reversed, which requires public policies at different levels (see chapter VI). ICT goods trade is an example of carbon costs and economic benefits being unevenly distributed among developed and developing countries, as discussed in the next section.

b. Mining in the global electronics value and production chain

The mining supply chain is just the first stage in the overall global electronics value and production or supply chain. When considering the environmental impact of the production stage of the digitalization life cycle, it is important to situate materials consumption in the overall chain of the manufacturing of ICT products.

In terms of value, figure II.15 shows the smile curve that represents the different activities in the global ICT goods value chain. Higher value is added at the pre-production stage, which includes activities such as research and development or design, as well as at the post-production stage, which includes activities such as distribution, marketing, branding and other services. All these activities tend to take place predominantly in developed economies. The production stage, which concerns the mining and processing of minerals, manufacturing and assembly of final ICT goods, is the phase that carries the highest environmental and social burden, and takes place mainly in developing countries. This is also the stage that generates the lowest value addition.

A simplified representation of the electronics or ICT goods production or supply chain is presented in figure II.16, focussing on the physical production stage. Upstream, in the mining supply chain, there is exploration, development of a mine, extraction of minerals and then processing (smelting and refining) to enable the metal to be of an appropriate quality for manufacturing. The middle stream entails manufacturing components from the raw materials. Finally, downstream, the components are assembled into the final electronics or ICT goods.

As noted, the extraction of minerals occurs mainly in developing countries in Africa, Asia and Latin America. Minerals are subsequently transported, mainly to some

There is an "unequal ecological exchange" between developed and developing countries

[49] For more on ecologically unequal exchange, see UNEP and IRP (2024), UNCTAD (2022a); for LDCs, see Infante-Amate et al. (2022); Alonso-Fernández and Regueiro-Ferreira (2022); and for Latin America, see Palacios et al. (2018).

The production processes of digital devices are modular, but the products themselves are not

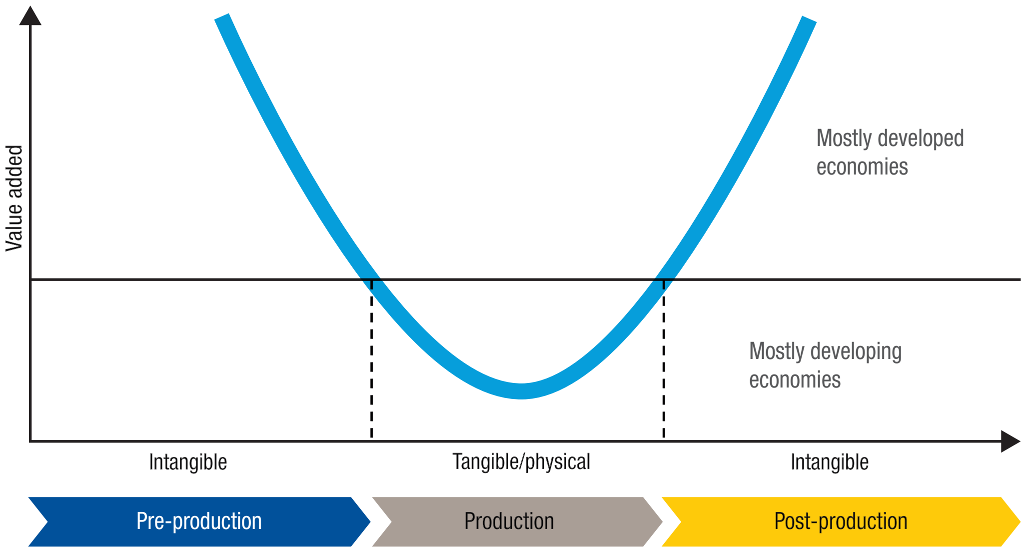
developed countries and China, to be refined. Components manufacturing primarily takes place in several Asian countries, while developed countries produce most of the higher technology content components (and therefore capture the higher value). Assembly predominantly happens in a number of Asian countries, including China, Malaysia, the Philippines, Singapore and Viet Nam (Brodzicki, 2021). This production chain also implies significant transport activity among the different countries, in which the various suppliers producing the multiple components and materials are located. It is estimated, for instance, that a smartphone travels several times around the world before it reaches final production.[50]

It should be noted that this representation is an oversimplification. Even if the figure is presented in a linear manner, the production processes in electronics and ICT products are highly complex. Each product may comprise hundreds of components, which in turn are made of multiple transition minerals, metals and other materials.

Therefore, the final production chain is a network of intermediary production chains for this multitude of components and for the different transition minerals included in each component.[51] According to Thun et al. (2022, 2023), ICT can be considered a "massive modular ecosystem" or an "ecosystem of ecosystems" in which standard interfaces allow linkages both within and between industries, allowing for rapid increases in scale and complexity. Thus, the production processes of digital devices are modular, but the products themselves are not. Greater modularity would facilitate repair of the products and replacement of components, as well as remanufacturing by reusing different components that still function (see chapter IV).

Considering the global distribution of the different stages of the value chain and the fact that the geographical physical production stage is where the least value addition occurs and where there is the highest environmental cost of materials

Figure II.15
The smile curve of global value distribution in ICT goods production

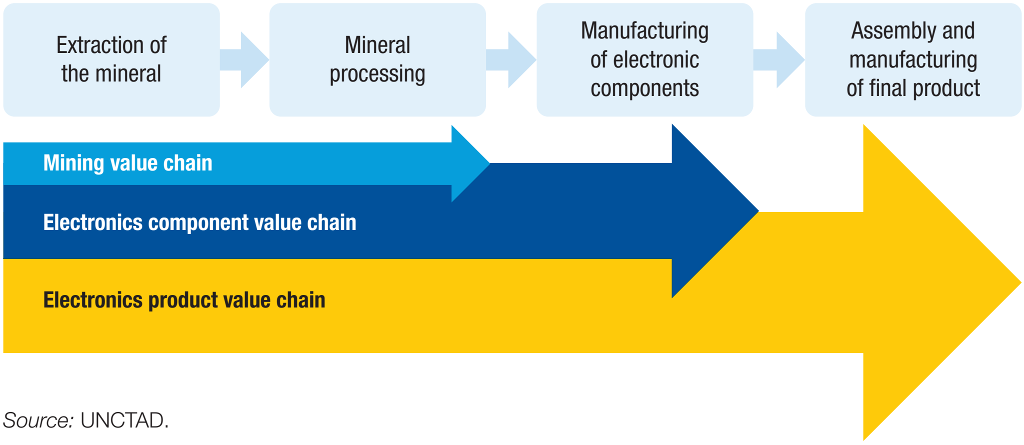


Source: UNCTAD.

50 See https://www.monde-diplomatique.fr/publications/manuel_d_economie_critique/a57189.

51 For more detailed information on supply chains for various minerals, for example for cobalt, see Cobalt Institute (2022) and for minerals in a particular developing region such as Latin America, Lagos et al. (2021). In the case of components, Bridge and Faigen (2022) provide a detailed assessment of the lithium-ion battery production network, Obaya and Céspedes (2021) look at implications for countries in the "lithium triangle". Moreover, the semiconductor supply chain is mapped by Thadani and Allen (2023) and Varas et al. (2021).

Figure II.16
The global electronics production chain



Source: UNCTAD.

extraction and manufacturing, trade in ICT goods provides an example of "unequal ecological exchange". According to Zhou et al. (2022), carbon losses and economic gains induced by ICT trade are unevenly distributed among regions. Eighty-two per cent of carbon emissions are attributed to emerging regions, while developed regions benefit from 58 per cent of the value added. This carbon-economic inequality arises from the fragmentation of international production.

4. Trade dependence and diversification: The two sides of transition minerals

Excessive dependence on trade in transition minerals, whether on the export or the import side, is a risk that needs to be addressed. One way to mitigate this risk is to diversify products and partner countries. In order to climb the value chain, countries that depend heavily on exports of transition minerals need to diversify exports towards products of higher value. Countries with excessive dependence on imports of transition minerals can reduce the risks by diversifying supplies from several countries. As transition minerals have become more important on the international agenda, many countries are implementing policies to this end.[52]

a. Countries exporting transition minerals

From the perspective of transition mineral-exporting countries, which are often developing countries, dependence refers to the high share of these commodities in their total production and exports, as shown in figure II.13 (UNCTAD, 2023e). Consequently, their overall economic growth, foreign exchange earnings and government revenues are highly dependent on the evolution of this sector. As a result, they are vulnerable to external conditions and shocks that can affect the demand for transition minerals. Moreover, given the high volatility of minerals and metals prices, the stability of the economy may be affected by boom and bust cycles.

Policymakers in developing countries, notably in LDCs, have long been concerned about the high reliance on the production and export of a few primary commodities. A shift away from such dependence requires diversification of the production and export structure in a country, as a development path.[53] Diversification towards manufacturing

[52] See https://www.iea.org/reports/critical-minerals-policy-tracker and https://www.iea.org/policies?topic=Critical%20Minerals.

[53] Addressing commodity dependence through diversification and structural transformation has been at the core of the work of UNCTAD throughout its 60 years of existence. See United Nations (1964a) and UNCTAD (2012, 2019b).

Developing countries should aim to capture, manage and use the proceeds from exported minerals to **achieve structural transformation**

activities is a way to reduce the dependence of developing countries on the production and export of primary commodities, while easing constraints in the balance of payments that affect development, by replacing imports or by increasing export earnings (United Nations, 1964b).

Diversification implies moving away from low productivity and value-added products to higher productivity and value-added production and exports (UNCTAD, 2022b). This means an increase in the share of manufactured goods, resulting in higher value addition in the domestic economy across total production and exports. Thus, while in absolute terms the extractive mining sector, which may generate relatively low value addition, can still grow, the higher value-added manufacturing and services sectors should grow at a greater pace.

Development policies should aim to capture, manage and use the proceeds arising from the production and exports of transition minerals to diversify the production and export structure and achieve structural transformation. Section E further elaborates on opportunities for developing countries that may emerge from the surging global demand for transition minerals.

b. Countries importing transition minerals

From the perspective of countries that are dependent on imports of transition minerals from a few countries, diversification may involve searching for alternative sources from which to secure supplies. This would reduce the risks related to potential supply disruptions. Some countries may also explore ways to boost domestic production.

The security of transition mineral supply chains has emerged as a priority for many countries (Shiquan and Deyi, 2023), which has been coupled with a proliferation of national strategies to secure supply.

In order to secure access to transition minerals and diversify supply sources, the United States and the European Union, among other mostly developed economies, have adopted industrial policies related to transition minerals and the industries that use them, including the electronics sector. This has led to support for the battery and semiconductors sectors, among others. This can be seen as representing a change in the focus of international economic relations from economic efficiency towards economic security or from "just in time" to "just in case" approaches in the global supply chain.[54]

Various measures have been taken to make value chains relying on transition minerals more resilient, both internationally and domestically, and to achieve higher levels of self-sufficiency and sovereignty, as well as control over production in critical sectors.[55] Moreover, several countries are seeking alliances and partnerships at the international level, with transition minerals-exporting countries providing possible alternative supply sources.[56]

At the domestic level, for example, the United States aims to secure a "made in America" supply chain for critical minerals" (United States, 2022a). Moreover, the 2022 Inflation Reduction Act establishes the shares of each critical mineral that have to be mined or processed (or recycled) in the United States, or in a country with which the United States has a free trade agreement. This share starts at 40 per cent in 2023, to reach 70 per cent in 2027. This is tied to the provision of tax credits for electric vehicles.[57] Similarly, the act awards a tax credit equal to 10 per cent of the cost of production to incentivize the domestic production of various components, including applicable critical minerals used in renewable energy generation, storage and related manufacturing.

54 See, for instance, https://www.ft.com/content/8a7cdc0d-99aa-4ef6-ba9a-fd1a1180dc82; and Zhang and Ha Doan (2023).

55 A de-risking approach was endorsed by the Group of Seven in their communiqué of May 2023: "We are not decoupling or turning inwards. At the same time, we recognize that economic resilience requires de-risking and diversifying" see Group of Seven (2023).

56 For reviews of different policies adopted by various countries to secure the supply of transition minerals, see Lazard (2023); OECD (2023b); Passi (2023) and Sancho Calvino (2022).

57 See https://home.treasury.gov/news/press-releases/jy1379.

The European Union Critical Raw Materials Act was adopted by the Council in March 2024.[58] This act sets out a range of benchmarks for 2030 related to the strategic raw materials value chain and to diversifying European Union supplies, as follows:

- European Union extraction capacity covers at least 10 per cent of annual domestic consumption;
- European Union processing capacity covers at least 40 per cent of annual domestic consumption;
- European Union recycling capacity covers at least 25 per cent of the annual domestic consumption;
- No third country to provide more than 65 per cent of the annual domestic consumption of each strategic raw material in the European Union.

Securing the supply of critical raw materials features high on the overall new industrial strategy of the European Union (Ragonnaud, 2023). Moreover, both the United States and the European Union have adopted “chips acts” to support the domestic production of semiconductors, recognizing these as a critical component in the electronics supply chain. They have also considered measures aimed at increasing the domestic supply of batteries.[59] Industrial policies are increasingly used around the world to promote the use of electric vehicles.[60]

Beyond the domestic perspective, at the international level, many countries are looking abroad to secure access to transition minerals from alternative exporting countries. There is a trend towards creating alliances or partnerships with countries that may be considered “friends” or “like-minded”, to allow for friendshoring of mineral production. Countries are actively engaging in “raw materials diplomacy” (Müller, Saulich, et al., 2023; Szczepański, 2021), in search of strategic agreements with reliable partner countries for the responsible and sustainable supply of transition minerals. Alliances are also being established in the private sector, for example, among electric vehicle and battery manufacturers.

One example of such an alliance is the Mineral Security Partnership, a multilateral forum launched in June 2022 by the United States, the European Union and nine partner countries.[61] These economies are mainly dependent on mineral imports (Majkut et al., 2023). The objective of this partnership is “to ensure that critical minerals are produced, processed and recycled in a manner that supports the ability of countries to realize the full economic development benefit of their geological endowments”.[62] At the bilateral level, the United States has signed a critical minerals agreement with Japan, and is planning similar agreements with the European Union and the United Kingdom (White & Case, 2023).

Most of these alliances seem to be taking place, or are being planned, among developed countries, mainly transition mineral importers, although Australia and Canada are also participating in international partnerships.[63] Australia has a partnership with India, which is also mostly a mineral importer (Australia Trade and Investment Commission and Deloitte India, 2021). From

Beyond expanding domestic mining, many countries are looking abroad to secure access to transition minerals from alternative exporting countries

[58] See https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en, https://www.europarl.europa.eu/RegData/etudes/ATAG/2023/754638/EPRS_ATA(2023)754638_EN.pdf, and https://www.consilium.europa.eu/en/infographics/critical-raw-materials/. The overall approach of the European Union on transition minerals is reviewed in European Parliament, Directorate General for External Policies of the Union et al. (2023).

[59] For semiconductors, see United States (2022b) and for the European Union Chips Act, see https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en. For batteries, see Federal Consortium for Advanced Batteries (2021) and European Court of Auditors (2023).

[60] See the chapter “Policies to promote electric vehicle deployment” in IEA (2021c).

[61] By March 2024, partners comprised Australia, Canada, Estonia, Finland, France, Germany, India, Italy, Japan, Norway, the Republic of Korea, Sweden, the United Kingdom, the United States and the European Union. See https://www.state.gov/joint-statement-of-the-minerals-security-partnership/.

[62] See https://www.state.gov/minerals-security-partnership/.

[63] For critical minerals partnerships for Canada, see https://www.canada.ca/en/campaign/critical-minerals-in-canada/our-critical-minerals-strategic-partnerships.html.

Basing partnerships on equity could help ensure mutual benefits and allow for **domestic value addition and structural transformation in developing countries**

this perspective, these alliances may be more focussed on creating a "buyers' club" (Lazard, 2023; Lu, 2023a; Pilch, 2023). For these alliances to be beneficial to both developed and developing countries, they need to focus on ensuring that supply is socially responsible and environmentally sustainable, while leading to developmental benefits in exporting developing countries.

Countries are also starting to look at partnerships to secure transition minerals from exporting developing countries. For example, in the context of the Community of Latin American and Caribbean States Summit held in July 2023, a memorandum of understanding was signed to establish a partnership between the European Union and Chile regarding sustainable raw materials value chains.[64] By mid-2024, the European Union had completed sustainable critical raw materials partnerships with twelve partner economies across three continents in the context of its global gateway.[65]

There is a risk that such alliances, mostly among developed countries importing minerals, may result in even more asymmetrical negotiating power and be detrimental to the interests of countries exporting transition minerals. This would risk aggravating the historically unequal positions of developing countries and their ability to negotiate the supply of minerals to developed countries.

Basing partnerships between developed countries and developing countries exporting transition minerals on equity could help ensure mutual benefits and allow for domestic value addition and structural transformation in such developing countries (Andreoni and Roberts, 2022; de Brier and Hoex, 2023). This would represent a move towards reducing persistent inequalities and asymmetries in this sector that have negatively affected developing countries.

At present, geopolitical tensions among major powers are particularly relevant for transition minerals and the ICT sector. In 2023, China banned exports of some rare earth elements, as well as their processing technologies, both of which are critical for semiconductor production. This was reportedly in response to the United States, the Kingdom of the Netherlands and Japan banning exports of some technologies critical for the production of electronic products in China.[66]

An escalation of tensions in trade and global supply chains could have various adverse effects.[67]

Significant resources and capital invested in developing production capacities for transition minerals and ICT products in countries that do not succeed in achieving technological leadership would be wasted. This could lead to unnecessary extraction of natural resources and environmental damage, to the extent that the production processes associated with these industries have negative environmental impacts. Alternatively, such resources and capital could be better used to address global development challenges in a coordinated manner. Overall, international cooperation and solidarity for inclusive and sustainable development would be a preferable option.[68]

64 See https://ec.europa.eu/commission/presscorner/detail/en/IP_23_3897.

65 See https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/raw-materials-diplomacy_en.

66 See https://www.ft.com/content/5b031db7-23dd-43d3-afe1-cef14817296f, and https://www.reuters.com/technology/us-secures-deal-with-netherlands-japan-china-chip-export-limit-bloomberg-2023-01-27/.

67 The Munich Security Report 2024 raises concerns about potential lose-lose dynamics (Munich Security Conference, 2024).

68 On resources rivalries, as a potential cluster of interrelated environmental, geopolitical and socioeconomic risks related to the supply of and demand for natural resources, see WEF (2023), which discusses four hypothetical futures for 2030: resource collaboration, resource constraints, resource competition and resource control. All futures, even resource collaboration, would face significant challenges. The most confrontational future, that of resource control, could lead to aggravating self-perpetuating and compounding global polycrises.

E. Opportunities for developing countries

Surging demand for transition minerals presents opportunities for developing countries, which are major producers and exporters of these minerals, to leverage the domestic availability of such resources to generate long-term added value and development. Africa and Latin America hold significant untapped minerals potential that could be used for inclusive and sustainable development purposes.

Many developing countries, particularly LDCs, need to overcome significant challenges linked to structural capacity constraints, for example in terms of infrastructure and energy and the limited availability of financial resources, relevant skills, knowledge and technology, as well as institutional and governance capacities (UNCTAD, 2022a).

Moreover, the international trade and investment context should be supportive for developing countries in order that they may be better equipped to benefit from their mineral resources. Foreign direct investment plays a major role in complementing often insufficient domestic resources for minerals extraction. This has led to power imbalances and asymmetries among Governments and populations in producing countries and mining companies, often with the result of an unequal distribution of rents from minerals resources. This international context has favoured a model in which developing countries well-endowed with natural resources become “locked in” as exporters of unprocessed and low value-added raw materials and importers of processed manufactures with higher value added. Developing regions, such as sub-Saharan Africa and Latin America, are major exporters of transition minerals, mostly in their unprocessed form. These regions import more than 50 per cent of their electronics consumption needs, mainly from the Asia and Pacific region, including China (Jeongmin et al., 2022).

Lessons from past “extractivist” experiences, during which developing countries hardly benefited from their mineral resources, are relevant for the emerging transition mineral boom. Avoiding a new scramble for resources requires a move away from previous extractive dynamics, so that mining can function more as an engine for structural transformation and development in developing countries (Mazzucato, 2023). Within this path to development, mineral resources can stimulate a process of dynamic interaction, or a virtuous circle, between minerals production and export, through economic diversification, including by increasing manufacturing (Anzolin, 2021; Freytes and O’Farrell, 2021; UNCTAD, 2016). This could help to alter traditional global trade patterns, and improve the position of developing countries as exporters of higher value mineral-based products.

There is a key role for Governments in developing countries to apply proactive policies to tackle constraints and build capacities, to move up the mining and related manufacturing value chain. The mineral resources sector can contribute to inclusive and sustainable development by providing financial resources for productive investment, and by generating various linkages with and spillovers to the overall economy. This would add value and steer diversification towards structural transformation, growth and employment creation. Economic policies need to be directed towards these objectives (AfDB, 2023; UNCTAD, 2016) (see also chapter VI).

Some developing countries that export transition minerals are already exploring the potential of, and moving into, the production of higher value-added goods. For example, they are seeking to add value by processing minerals, manufacturing intermediate goods such as precursors, batteries and, in the last term, even creating a regional value chain for manufacturing final products such as electric vehicles and smartphones

International trade and investment context should be supportive for developing countries to be better equipped to benefit from their mineral resources

A regional approach may allow developing countries to better harness their mineral resources

(Müller, Schulze, et al., 2023). This shift is in particular being observed in Africa, mainly in the Democratic Republic of the Congo with regard to cobalt, but also other minerals.[69] UNCTAD (2023f) shows that large reserves of critical minerals in Africa that are vital for the global supply chains of high technology-intensive industries could turn African economies into potential key suppliers of parts and components in sectors such as electronics and automotives.

In Latin America, lithium can play a major role, with significant potential for adding value to production in the three countries in the "lithium triangle" (ECLAC, 2023). In Asia, where the trade pattern is more diversified, Indonesia has imposed an export ban on raw nickel ore in order to increase domestic processing and value addition, including towards battery manufacturing (Huber, 2022).[70] The Indonesian strategy, although challenged at WTO, appears to be successful, attracting foreign investment and increasing downstream activities.[71] By mid-2023 the export ban was also extended to bauxite ore.[72]

Beyond national policies, regional and international cooperation and support are needed to ensure the necessary fiscal and policy space for structural transformation and development. A regional approach may allow developing countries to improve their bargaining power with foreign investors, expand markets and achieve the necessary scale. Moreover, cooperation can help with pooling resources for research and development, as well as infrastructure development. This would promote the emergence of regional mining-related value chains.[73] For example, in Africa, the African Continental Free Trade Area can be leveraged to increase value addition in transition minerals (AfDB, 2023; Baskaran, 2022; Cust and Zeufack, 2023). Moreover, several regional organizations are working towards preparing an African green mineral strategy (Africa Natural Resources Management and Investment Center (ANRC), 2022).

Internationally, the agreement at OECD in October 2021 to set out a global minimum tax on multinational companies is a step in the right direction (IISD and ISLP, 2023). Moreover, in the emerging global geopolitical context, where competition is increasing for access to transition minerals in developing countries, these countries can benefit from a wider choice of investors. They should not be compelled to choose among sources of foreign direct investment. Rather, they should leverage this competition to negotiate the most favourable conditions that align with their development objectives. For this to happen, as noted, partnership agreements and resource diplomacy efforts to secure access to transition minerals by developed countries need to be mutually beneficial, unlike past experiences. This would entail boosting value addition in developing countries that produce these minerals. For example, the United States signed a memorandum of understanding with the Democratic Republic of the Congo and Zambia to strengthen the electric vehicle battery value chain.[74] Similarly, the European Union aims to contribute to sustainability and local value addition in developing countries in the context of the global gateway (Wouters, 2023).

As transition mineral-importing countries have been creating alliances or "buyers' clubs" that could potentially weaken the bargaining position of developing countries exporting such minerals, the latter may in turn create "sellers' clubs".

[69] See Ahadjie et al. (2023); Diene et al. (2022); Karkare and Medinilla (2023); Mavhunga (2023); Müller (2023b) and World Bank (2023).

[70] See https://www.ft.com/content/0d2fba79-940f-4a28-8f4f-68f1e755200f; https://epsnews.com/2023/07/20/mineral-rich-nations-seek-to-raise-their-supply-chain-profiles/; and Lu (2023b).

[71] See https://foreignpolicy.com/2024/02/13/indonesia-election-nickel-economy-energy-jokowi-prabawo/ and https://eastasiaforum.org/2023/09/28/assessing-nickel-downstreaming-in-indonesia/.

[72] See *Xinhua*, Roundup: Indonesia pushes ahead with bauxite export ban despite controversy, 21 June 2023.

[73] See Grynspan (2022); Bridle et al. (2021) and Müller (2023b).

[74] See https://www.state.gov/the-united-states-releases-signed-memorandum-of-understanding-with-the-democratic-republic-of-congo-and-zambia-to-strengthen-electric-vehicle-battery-value-chain/.

Some approaches similar to those of the Organization of the Petroleum Exporting Countries have been proposed for minerals such as nickel and lithium (Hendrix, 2023).

Finally, international support is needed, particularly in LDCs, in the form of financial support and technical assistance so that they can overcome structural constraints and build capacity for diversification and structural transformation.

Taken together, there is significant potential for many developing countries to take advantage of the positive demand prospects for transition minerals and achieve sustained, inclusive growth. But minerals extraction also involves environmental and social risks and costs that need to be considered, as discussed in the next section.

F. Impacts of the production phase on the planet and people

Since the production of digital devices and ICT infrastructure requires the intensive use of minerals and metals, this life cycle phase is responsible for the environmental and social impacts associated with mining such minerals and metals.[75] Mining activities frequently have negative impacts on both the environment and surrounding communities. They are also often intricately intertwined with human rights implications. These issues are exacerbated in developing countries,[76] particularly in LDCs, which have limited capabilities for addressing negative externalities from mining (Lèbre et al., 2020). A study focusing on the extraction, processing, use and disposal of seven metals (aluminium, copper, iron, lead, nickel, manganese and zinc) forecasts that total environmental impacts could more than double, and in some cases even quadruple, by 2060 (OECD, 2019).

Environmental and social impacts, including on human rights, vary by type of mineral and metal, and geographical location. However, it is possible to highlight some general impacts that are typically observed. These are often interconnected; more often than not, environmental implications from mining are linked to social impacts, and may have a knock-on effect on human rights. Policy responses to some of the social and environmental challenges noted in this section are further considered in chapter VI.

Some of the major impacts observed include the following:[77]

- *GHG emissions and energy use:* Mining activities are energy-intensive, at both the extraction and processing stages, and mostly rely on fossil fuel energy. It is estimated that emissions associated with primary minerals and metals production were equivalent to approximately 10 per cent of total global energy-related GHG emissions in 2018 (Azadi et al., 2020). Achieving the transition to a sustainable socioeconomic pathway requires additional substantial efforts to reduce GHG emissions in this sector (Yokoi et al., 2022). Moreover, as mineral ores decline due to reserves becoming less easily accessible, emissions and energy demand from mining will increase, as will most of the environmental impacts listed in this section.

Environmental implications from mining are often linked to social impacts, and may have a knock-on **effect on human rights**

[75] As noted, data on the mineral extraction required for digital equipment manufacturing are not available. Therefore, it is not possible to accurately determine the part of the environmental and social impacts that can be attributed to digitalization.

[76] See https://unctad.org/news/developing-countries-pay-environmental-cost-electric-car-batteries.

[77] For more detailed discussions of the environmental and social impacts of mining, see Bolger et al. (2021); IEA (2021a); IRENA (2023); UNEP and IRP (2020b) and United Kingdom, Parliamentary Office of Science and Technology (2022).

- *Water use:* Extraction and processing operations require significant amounts of water. Many of these extractive activities take place in areas already experiencing water stress (Luckeneder et al., 2021). Heavy water use by the mining companies can complicate water access for the local population and have a negative effect on wildlife. For example, in lithium extraction from brines, huge amounts of groundwater are needed to pump out brines from drilled wells; estimates show that producing one ton of lithium requires almost 2 million litres of water (UNCTAD, 2020). Water issues in mining relate to both quantity and quality (IGF, 2022).
- *Pollution of soil, air and water*: Mining generates waste and toxic chemicals as by-products. These are generally disposed of in mine tailings that, if not properly managed, can lead to soil and water pollution as a result of leakages, as well as land erosion. Moreover, mining can release toxic substances (such as mercury) which are very harmful for the environment and the population. This toxicity can include fine particles and dust that contain toxic and heavy metals. Improper treatment of mine tailings can lead to negative environmental and humanitarian impacts. For example, rare earth elements incur high environmental costs not only in terms of water use but also because their extraction can acidify soil and groundwater, generate radioactive material, or cause heavy metal pollution from solid waste. These impacts are aggravated because such minerals are widely scattered over the Earth's crust, which makes mining difficult and expensive. Separation and processing also require the use of chemicals that generate toxic externalities (Zapp et al., 2022).[78]
- *Ecosystems and biodiversity*: Negative impacts can be particularly severe when mining activities take place in areas that are protected or that have high biodiversity value, threatening vulnerable ecosystems. By mapping mining areas and assessing their spatial coincidence with biodiversity conservation sites and priorities, Sonter et al. (2020: 1) find that "mining potentially influences 50 million km^2 of Earth's land surface, with 8 per cent coinciding with Protected Areas, 7 per cent with key Biodiversity Areas and 16 per cent with Remaining Wilderness".
- *Deforestation:* Mining is considered to be the fourth largest driver of deforestation. Kramer et al. (2023) highlight that over the past two decades, the direct deforestation impacts of mining have been highly concentrated, with almost 84 per cent of total direct mining-related deforestation taking place in only 10 countries. They estimate that computers and electronic products have driven 5 per cent of all deforestation worldwide related to mining expansion. It is also estimated that 44 per cent of all operational mines are in forests. In absolute terms, most forest mining takes place in large countries, including Brazil, Canada, China, the Russian Federation and the United States. However, if land area size, economic importance and forest cover are considered, major countries in forest mining include Brazil, the Democratic Republic of the Congo, Ghana, Zambia and Zimbabwe. Moreover, more than half of all existing forest mining occurs in lower- or middle-income countries (World Bank, 2019). For example, in the Amazon rainforest in Brazil, 11,670 km^2 of deforestation between 2005 and 2015 was caused by mining, which represents about 9 per cent of the total loss of forest in the Amazon during the period (Saracini, 2023). Overall, it is estimated that mining accounts for about 7 per cent of annual forest loss in developing countries (United Kingdom, Parliamentary Office of Science and Technology, 2022).
- *People's health and safety*: The pollution of soil, air and water can lead to impacts on population health in the mining

[78] Golroudbary et al. (2022) show that an increase by 1 per cent of green energy production causes a depletion of rare earth elements reserves by 0.18 per cent and increases GHG emissions in the exploitation phase by 0.90 per cent and that between 2010 and 2020, the use of permanent magnets resulted cumulatively in 32 billion tons CO_2e of GHG emissions globally.

areas affected by the effects of toxic substances. In addition to potentially reducing access to water, pollution may lead to drinking water shortages.

- *Communities, particularly indigenous peoples*: Mining activities lead to changes in land use, which imply displacements of communities living in the corresponding areas, with significant disruptions to livelihoods, ways of life and cultural ties to the land. In considering the human rights implications of mining, indigenous communities are seen to be particularly impacted.[79] In a sample of 5,097 energy transition minerals projects, Owen et al. (2022) found that 54 per cent of projects were "located on or nearby Indigenous peoples' lands".
- *Working conditions*: Some mining activities are characterized by poor labour conditions, including lack of voice and freedom to participate in unions, as well as limited rights and access to social protection. In some cases, activities have been found to involve forced labour, child labour and human trafficking. Hazardous working conditions may also be related to unsanitary environments, as well as overall violations of safety, which may lead to injuries, illnesses, disability or death. According to ILO, when the number of people exposed to risk is taken into account, mining is the most hazardous occupation.[80] Mining can also lead to significant inequality, particularly for women (box II.2).
- *Artisanal and small-scale mining (ASM)*: While much of global mining occurs through large-scale mining, for some countries and minerals, such as the mining of cobalt in the Democratic Republic of the Congo, ASM plays a significant role. It is estimated that in 2020, 44.75 million people working across more than 80 countries made their living in ASM. This represents a threefold increase of people in this sector over the past 20 years. Sub-Saharan Africa has the largest proportion of such miners, accounting for one fourth of that number.[81] ASM is an important source of income for many poor and marginalized people. Such miners operate within an informal context, with low levels of safety, poor working conditions and instances of exploitation, even slavery. Weak management further exacerbates environmentally harmful activities at such mines, making them even more polluting than other forms of mining. Children are often found working in ASM mining.
- *Child labour in mining*: According to the ILO (2019a), more than 1 million children work in mines and quarries. This constitutes a serious violation of the rights of children because their health and safety are put at risk, and they are deprived of education. Due to its inherent dangers, ILO considers mining and quarrying hazardous work, and one of the worst forms of child labour. This problem is particularly acute in certain areas and minerals sectors, such as gold in Burkina Faso, Mali and the Niger, and cobalt and coltan mining in the Democratic Republic of the Congo.
- *Mining and conflicts*: If mining takes place in countries with armed conflict situations, there is the risk that it may help finance different parties in the conflicts. Mining could be the cause of a conflict and at the same time enable conflicts to continue. Beyond armed conflicts, resistance to the negative impacts of mining may give rise to conflicts among affected populations, with the mining companies or with the Governments concerned.[82] From a sample of 1,044 environmental conflicts affecting indigenous peoples, Scheidel et al. (2023) find that mining is the primary sector driving those conflicts, accounting for 24.7 per cent of the total.

[79] See https://www.un.org/development/desa/indigenouspeoples/about-us.html.

[80] See https://www.ilo.org/global/industries-and-sectors/mining/lang--en/index.htm.

[81] See World Bank (2020, 2023) and https://www.worldbank.org/en/news/feature/2019/06/19/shining-a-light-on-a-hidden-sector and https://delvedatabase.org/.

[82] See https://ejatlas.org/.

Box II.2
Women and mining

According to ILO (2021), among some 21.4 million workers employed in mining and quarrying in 2019, only 3.1 million were women. This represents less than 15 per cent of the total. By contrast, women tend to be disproportionately affected by the negative economic, social and environmental externalities of these activities.

"Women and the mine of the future" is a collaborative project designed to increase understanding of the status quo for women in mining, so that stakeholders can anticipate, assess and address gendered impacts as the mining industry evolves. Project partners include the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, International Women in Mining, ILO, the German Agency for International Cooperation, the Environmental Governance Programme operated by the Swedish Environmental Protection Agency and UNDP. It looks at a sample of 12 countries to uncover the gender-disaggregated employment profile for large-scale mining, focusing on women and their occupations in the sector. The countries included are Argentina, Australia, Brazil, Canada, Chile, Colombia, Ghana, Mongolia, Peru, South Africa, Sweden and Zambia.

The main conclusions from the global report for this project include the following:

- Large-scale mining is one of the economic sectors most over-represented by men. Among these countries, Sweden shows the highest share of women's participation in total mining employment, at 25 per cent, while Peru accounts for the lowest, at 9 per cent. Nevertheless, the share of women employed in large-scale mining is gradually increasing, although at a slow pace. Moreover, women in the mining sector are more vulnerable to losing their jobs during economic downturns compared to men.
- Working conditions in the mining sector are not conducive to women's employment. Basic facilities and equipment are still designed for men's needs and there are challenges to full implementation of parental leave. Moreover, violence, harassment and gender-based discrimination are prevalent.
- Women are underrepresented in certain mining occupations, for example as technicians and associated professionals, craft and related trade workers and plant and machine operators, while they are overrepresented in others, such as clerical and support positions. They are also less represented in the "professional" occupational category, except for business and administration, as well as in professional, managerial and leadership positions.
- Barriers remain for women to obtain mining-specific skills and education. Overall, women in mining have a higher educational attainment than men. However, they have fewer technical and vocational qualifications. Furthermore, women are less likely to receive on-the-job training and apprenticeship opportunities than men.
- Women leave large-scale mining at a younger age. This is related to the occupations and the type of work they perform, and due to a variety of other reasons, including non-inclusive working conditions and lack of career growth.
- There is a persistent and significant pay gap in the mining workforce: women employees earn lower wages, despite their higher level of education. This gap is larger for better paid occupations. Moreover, women workers work fewer hours.

Source: UNCTAD, based on IGF (2023).

- *Human rights implications*: All of the above give rise to imbalances, injustices and possible violations of human rights. The transition minerals tracker of the Business and Human Rights Resource Centre monitors human rights implications of mining for six key technology-related minerals: cobalt, copper, lithium, manganese, nickel and zinc. It identified 510 allegations of human rights abuses from 2010 to 2022, including 65 in 2022. Over two thirds of all allegations are from just 14 companies, which are among the largest and most well-established companies in the extractive sector and from all around the world (Avan et al., 2023).[83]

Responding to concerns about how the sourcing of transition minerals may further exacerbate child labour, modern slavery, poverty and social exclusion, as well as worsening energy poverty levels and constraining access to land and other resources to vulnerable and historically excluded groups, the United Nations Working Group on the issue of human rights and transnational corporations and other business enterprises called for inputs on the extractive sector, just transition and human rights. This recognized the multitude and complexity of human rights issues that extractive sectors face. In an attempt to answer the question of how to achieve a human rights-based and just transition, the resulting report provided practical guidance to States, business enterprises and other stakeholders on the best ways to design and implement just, inclusive and rights-based transition programmes, investments and projects.[84]

In sum, the extraction of transition minerals should not come at the expense of the natural environment, local communities, human rights and peace. In recent years, there has been some progress in this regard, following technological advances, increasing awareness and concerns worldwide of the negative impacts of mining, as well as regulations and, mostly voluntary, standards at different levels. However, pressures from the increasing demand for raw materials may lead authorities to relax environmental impact assessment procedures, reduce permission times or weaken other environmental requirements for mining operations (Amigos de la Tierra and CIRCE, 2023). Thus, there is still a long way to go in properly and fully tackling harmful environmental, social and human rights impacts in the mining value chain. In the future, sourcing minerals and metals that are increasingly demanded by society will require the implementation of procedures that go beyond existing ecological, economic and social requirements and practices (Renn et al., 2022).

There is a need to balance the development of mining activities with benefits for producing countries, the rights of the local population and communities and the protection of the environment. This should apply along the entire value chain, which, beyond extraction, includes the processing of minerals and manufacturing the electronic products that contain such minerals (box II.3). Moreover, assessments of the environmental impact from mining should also consider transport, given that the different stages of the production of minerals, components and manufactured products take place in different countries around the world, before they are shipped to final markets.

> There is a need to balance the expansion of mining with the development benefits for producing countries, the rights of the local population and the protection of the environment

Supply chains of minerals and related electronics need to be properly governed at the national, regional and international levels, in an integrated and holistic way, to ensure that mining contributes to development in an inclusive, responsible and environmentally sustainable manner.

[83] For key human rights-related risks in the mining and metals sector, see https://www.unepfi.org/humanrightstoolkit/index.php.

[84] See https://www.ohchr.org/en/calls-for-input/2023/call-inputs-extractive-sector-just-transition-and-human-rights and https://www.ohchr.org/en/documents/thematic-reports/a78155-extractive-sector-just-transition-and-human-rights.

Box II.3
Environmental and social impacts of electronics manufacturing

Electronics manufacturing, particularly semiconductor production, is one of the most toxic industrial processes. More than 400 chemical products are used in semiconductor manufacturing. It also requires large amounts of purified water and generates wastewater that contains heavy metals and toxic solvents. The production of components and the final assembly of electronic devices often involve wasteful processes.

Contrary to the mining sector, in electronics manufacturing, women workers make up the majority of the labour force, although they are primarily engaged in assembly line processes. A study by ILO, the European Union and OECD highlights the following decent work challenges in this area:

- Excessive working hours;
- Workforces with high shares of temporary or contract workers to accommodate flexible production demands;
- Limited training;
- Low wages, with a disproportionately higher share of women workers severely impacted;
- Forced labour, especially in relation to migrant workers;
- Occupational safety and health risks such as exposure to chemicals, uncomfortable working positions, repetitive work motion and problems related to eyesight;
- Most workers not able to exercise their union and collective bargaining rights.

Source: UNCTAD, based on Electronics Watch (2020) and ILO et al. (2023).

G. Conclusions

This chapter has looked at the production phase of the life cycle of digitalization, with an emphasis on the mining and processing of transition minerals. It has shown that digitalization is a material-intensive process. The world is undergoing significant transformations, strongly marked by the low-carbon and digital technologies, which are highly intensive in terms of minerals and metals. Without such materials there cannot be digitalization. Demand for transition minerals reflects the rapid development of new digital technologies, which necessitates more and more devices and the continuous development of the digital infrastructure needed to support the changing ecosystem.

The resulting surge in the demand for transition minerals raises major geopolitical and developmental concerns and challenges. Following global supply chain constraints resulting from the pandemic and the war in Ukraine, some reorganization of global production is taking place; developed countries importing transition minerals and electronics manufactures aim to secure supplies, including by increasing domestic production and forging new alliances. Their focus has been rebalanced from economic efficiency towards economic security, with an emphasis on increasing minerals supply, either primary supply or secondary supply from recycling, rather than on reducing overall consumption.

From the perspective of developing countries, this can provide an opportunity for development, provided they are able to add more value to minerals (see chapter VI). This scenario should help to reverse past trade asymmetries, in which developing countries export raw minerals yet import higher value-added manufactures, together with the related ecologically unequal exchange. Moreover, mining, as well as ICT goods manufacturing, can generate environmental and social impacts in developing countries, including on human rights, and these need to be minimized.

Taken together, there is a race to increase mining all around the world, as well as the production of electronic goods. This is part of a broader race for economic, trade and technological leadership, whereby securing access to transition minerals becomes vital for survival in a low-carbon and digital era. This has led to a worldwide push to increase mining and electronics manufacturing. Huge amounts of investment and public support are also provided for increasing minerals extraction, as well as expanding the production of, for example, batteries, semiconductors and electric vehicles.

From a global perspective, there is a risk that this can lead to overmining and manufacturing overcapacity. There may be a waste of resources from many countries that have invested significant resources without achieving comparable benefits, that is, resources that could have been used for other developmental purposes. Thus, approaches that may be perceived to be strategic from a perspective of national economic security may not only negatively affect global economic efficiency but also environmental sustainability. A more balanced, comprehensive, global approach may be preferable, one that considers supply and demand aspects and combines the interests of developing and developed countries, exporters and importers, while aiming for more responsible and sustainable consumption and production.

Addressing the surging demand for transition minerals will require rethinking models of consumption and production, looking not only at the supply side of the minerals, in terms of increased primary supply from mines, and secondary supply from recycling, but also at the demand side, in terms of reducing excessive consumption. Considering the significant digital divides between developed and developing countries, and in the spirit of the principle of "common but differentiated responsibilities", there could be much more of a margin for consumption reduction in developed countries.

Some hopes are also placed on technological advances that may lead to increased resource efficiency or to mineral substitutes. For example, changes in battery chemistry may reduce the use of minerals such as cobalt or lithium. These can bring uncertainty for countries producing these minerals. Recycling digitalization-related waste is also a useful option to reduce the extraction of minerals. Moreover, as discussed in chapter IV, by following a circular economy logic, there are several options before recycling that can help reduce mineral consumption.

Such an approach will require changes in consumption and production to make digitalization more responsible and environmentally sustainable. This should be enabled, promoted and regulated by public policies, including regional and global governance, which are discussed in chapter VI.

Chapter III explores the next phase of the digitalization life cycle, the use phase.

Addressing the surging demand for transition minerals will require rethinking models of consumption and production

Annex to chapter II: Using thermoeconomics analysis to explain mineral depletion

Mineral depletion is the natural result of exponential behaviours and trends of consumption and growth.[85] At the current rate of extraction, in only one generation, humankind will have consumed as many minerals as during the entirety of human history. Moreover, the demand for minerals will have doubled or even tripled. In view of the growing demand for more minerals and metals to support the rapid development of low-carbon and digital technologies, it is important to pay attention to the volumes of resources that are extractable from the Earth. Some minerals are scarce but feasible to obtain, such as cobalt. Others are abundant but difficult and very costly to separate. Rare earth elements, for example, are more common than cobalt or copper, but costly to extract and separate. Others fall in the middle of this range.

As there is no economic theory that can give an objective value to the mineral wealth of the planet, economic analysis can be complemented with physics, and the principles of thermodynamics. "Thermoeconomics" combines ideas from thermodynamics and economics to measure materials transformation processes in energy units, instead of only in monetary units. This allows the analysis to go beyond subjective monetary value and the costs of mineral extraction, particularly as metals market prices fail to properly encompass the concept of mineral scarcity.

"Exergy" analysis is a valuable tool in assessing the depletion of mineral resources. The concept of exergy measures the quality and quantity of energy within a system. The exergy of an energy flow is the maximum amount of work that it can deliver (produce). In the case of minerals extraction, a scenario on Earth in which there is no concentration of minerals and, instead, there is maximum dispersion on the planet, would essentially constitute a state of bare, simple rock, or "thanatia", a resource-exhausted planet.[86] The concept of thanatia offers a baseline for assessing the concentration exergy of mineral resources. In terms of mineral concentration, any state beyond thanatia would have exergy. Thus, a mine becomes valuable because of its concentration of mineral resources. In the same way, the higher the concentration level, the higher the exergy. As mines are depleted, their mineral concentration approaches that of thanatia, leading to exponentially increasing costs of extraction.

While the Earth's crust is composed of minerals, it is only possible to extract those that are concentrated in deposits; the costs of extracting specific minerals or metals from bare rock would be unaffordable. However, concentrated mineral deposits are a geological rarity, representing only a small fraction of the outer crust, between 0.01 and 0.001 per cent. "Thermodynamic rarity", i.e. the amount of exergy needed to extract metals from ordinary rocks (thanatia), considers the concentration of minerals in the Earth's crust and the physical laws, based on real phenomena.[87]

[85] This annex pays particular attention to mineral resources in the earth before extraction. The analysis is based on research at the Centre of Research on Energy Resources and Consumption, Spain. See Almazán (2021); Calvo et al. (2016, 2017); Valero et al. (2021); Valero and Valero (2014, 2015).

[86] Thanatia, named after the Greek for "death state", is a hypothetical state explored in Valero et al. (2021).

[87] The second law of thermodynamics, also known as the entropy law, governs all physical systems. It implies that although the amount of energy remains constant, it becomes increasingly disperse, implying that everything will deteriorate until it cannot deteriorate any further.

In thermodynamic terms, going from a 1 per cent concentration to a 0.1 per cent concentration of ore requires at least 10 times more energy, water, tailings, infrastructure and ecosystem destruction for extraction. If ores with a richness of 0.01 per cent or 0.001 per cent have to be exploited. The energy requirements are at least 100 or 1,000 times higher compared to ores with 1 per cent concentration. Technology cannot exceed the efficiency limits set by thermodynamics; it can only approximate them.

Increased extraction has resulted in a continuous decrease in ore grades, particularly for those minerals that are least abundant. This decline has an additional effect that can also be explained through thermodynamics: energy, water, chemicals and environmental impacts increase exponentially as mines become depleted. Furthermore, as extractive mining remains highly reliant on fossil fuels, it can be anticipated that mining-associated emissions will also increase, at least in the short to medium term.

Unfortunately, discoveries of new deposits of certain minerals have notably declined in recent years. The projection of the theoretical year for reaching peak extraction for several minerals, if the stated resources were available, within the next 50 years, shows that 12 elements (including indium, lithium, gallium and nickel, which are essential for low-carbon and digital technologies) would reach peak production levels. The extension of the timeline to the next 100 years shows that approximately 30 elements would reach peak production levels. These projections consider current growth rates, which may be expected to accelerate further in line with the low-carbon and digital transition objectives and available resources, including speculative quantities of minerals not yet feasible to exploit. While there is uncertainty surrounding the availability of mineral reserves, exponential surge in demand is eventually bound to collide with finite resources. The future availability of minerals is at stake under current consumption trends.

In short, mineral depletion is not a matter of geological scarcity, given the vastness of the Earth’s crust, but rather a result of the increasing costs required to extract continuously declining mineral ore grades. Although technology may improve, it likely cannot be enough to remove the ever-increasing millions of tons needed to meet future mining demand. Eventually, the once concentrated and utilized materials end up discarded in landfills worldwide, dispersed in the Earth’s crust, in oceans or in the atmosphere (such as gases produced by burning fossil fuels).

By employing exergy analysis, it is possible to account for the irreversibility (in kilowatt hours (kWh)) that occurs throughout the entire life cycle of mineral extraction, processing and market distribution. This approach can enable a more comprehensive understanding of the energy losses and inefficiencies associated with the minerals supply chain. Furthermore, it can help estimate the future depletion of mineral deposits using the same units (kWh) and provide a clearer picture of the gradual exhaustion of mineral resources over time, helping to make informed decisions regarding resource management and sustainability. It is important to develop accurate and comprehensive indicators to effectively monitor the depletion of such resources. Such indicators should consider the objective reality of mineral depletion, the multi-metal nature of deposits and their broader environmental and societal impacts.

In this mineral depletion outlook, those who first implement low-carbon and digital technologies may not face significant scarcity issues. Prices may initially rise, although at manageable levels. However, as demand continues to increase, there may be substantial increases in prices, as mines become more and more depleted. Moreover, the degradation of the planet’s mineral wealth will have major impacts on the environment and humanity, especially for future generations.